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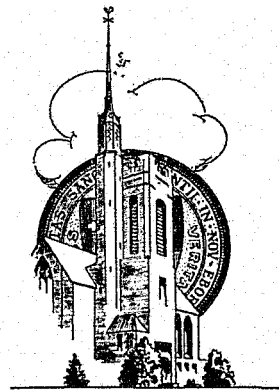
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BETWEEN LINEARS, TOTAL AND HAZY AREAS, AND
PETROLEUM PRODUCTION IN THE WILLISTON BASIN:
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INVESTIGATION OF RELATIONSHIPS
BETWEEN LINEARS, TONAL AND HAZY AREAS,
AND PETROLEUM PRODUCTION IN THE
WILLISTON BASIN - AN ERTS APPROACH

FINAL REPORT
August, 1975

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ABSTRACT

ERTS-1 imagery in a variety of formats has been used to locate linear, tonal and hazy features and to relate them to areas of hydrocarbon production in the Williston Basin of North Dakota, eastern Montana, and northern South Dakota. It is felt that lack of uniformity between images due to both seasonal and processing variations would make computer-enhanced mapping techniques inappropriate for a study as broad as this. For that reason derivative maps of rectilinear, curvilinear, tonal, and hazy features were made using standard laboratory techniques.

Mapping of rectilinears on both bands 5 and 7 over the entire region indicated the presence of a northeast-southwest and a northwest-southeast regional trend which (we feel) is indicative of the bedrock fracture pattern in the basin. Patterns produced by mapping curvilinears are less easily assessed, due in part to the fact that Pleistocene deposits cover two-thirds of the basin and produce numerous curved line and tone features not related to subsurface conditions.

Curved lines generally bound areas of unique tone. For that reason maps of tonal patterns repeat many of the boundaries seen on curvilinear maps. In most cases it has not been possible to assign a geological cause to tonal patterns although the reason for their distinct appearance on the imagery may be evident - ie., patches of cropland, river flood plains, etc. . Tones are best analyzed on spring and fall imagery in the Williston Basin.

Particular attention was given to "hazy" areas on the imagery. It is important to note that such areas are not consistent in either location or

appearance from image to image over the same region. For instance, an area which is hazy on a July, 1972 image will probably not be hazy on a July, 1973 image. This leads us to believe that hazy imagery has been caused by one (or more) of the following: 1) an artifact of processing; 2) atmospheric conditions such as haze close to the ground; 3) some local condition of soil moisture which is not the result of conditions at depth. At present we favor the idea that hazy areas are atmospheric phenomena.

The ability to use ERTS imagery as an exploration tool was examined in detail in four portions of the basin where petroleum and gas are presently produced: Area A - Bottineau Field; Area B - Nesson and Antelope Anticlines; Area C - Redwing Creek Region; Area D - Cedar Creek Anticline. It is determined that some tonal and linear features coincide with the location of present production in Areas C and D. In the remaining cases targets could not be sufficiently well defined to justify this method. Numerous "anomalies" could be identified in Areas A and B, but we could not establish any correlation between the "anomalies" and areas of known production. Some producing sites were within hazy areas, others were not. We do not feel that there is any correlation between the presence of hydrocarbons at depth and the occurrence of hazy areas.

ERTS imagery can be used to identify targets for hydrocarbon exploration. We believe it offers the geologist an additional perspective which, when employed in conjunction with other tools, can serve well for rapid examination of large areas in a variety of formats. Each user must develop his own methods for its use.

SCOPE

The following report is a summary of the pertinent interpretations derived from study of ERTS-1 imagery of the Williston Basin in North and South Dakota and eastern Montana as related to hydrocarbon production and exploration. Work has been conducted by the authors under grant NSG-5018 from NASA. The study focused upon attempts to recognize on ERTS-1 imagery features of known or unknown origin which may be geologically related and may thus have interpretive value to persons involved in petroleum exploration. Attempts to locate targets for future exploration are beyond the scope of this project.

Efforts to identify "hazy" anomalies (Collins, et al., 1974) in the region were given particular attention due to interest generated in them by studies in the Anadarko Basin of Oklahoma (Collins et al., 1974). Linear and tonal features were examined in detail as well.

TECHNIQUES, PROBLEMS, AND LIMITATIONS

Imagery supplied through NASA Goddard Spaceflight Center (GSFC) covered most of the Williston Basin south of lat. 49°N. and east of long. 104° 30'W. as delineated in Figure 1. Seasonal coverage was not complete due to restrictions imposed by cloud cover at several times of the year. MSS bands 4, 5, 6 and 7 imagery in both black and white transparency and print formats was available for nearly the entire region whereas color composite images were available for only some of the image areas.

The study has been conducted using visual, rather than computer-

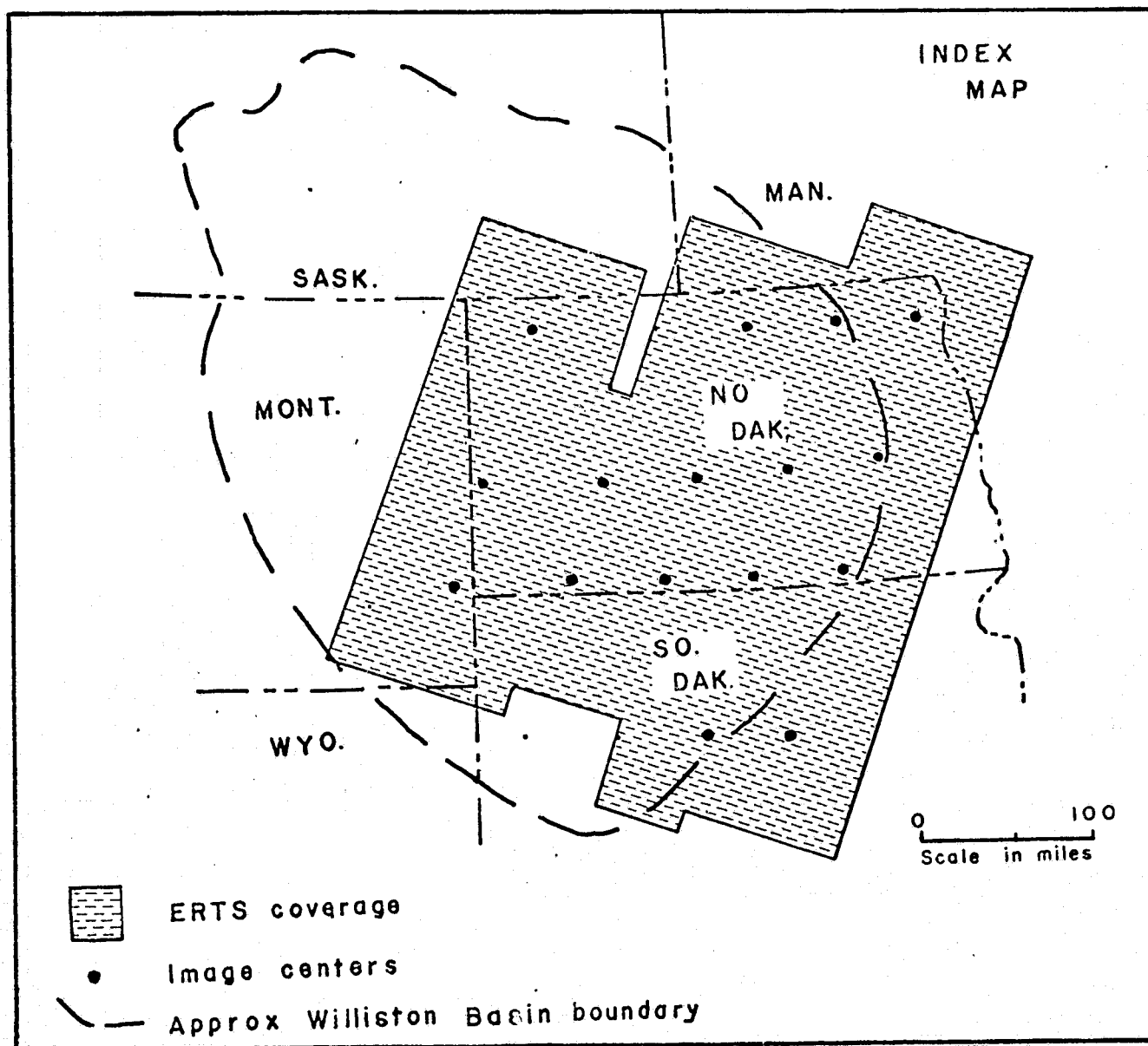


Figure 1. Index map giving the outline of the Williston Basin and showing the extent of ERTS-1 coverage used for this study.

enhanced techniques because of a lack of uniformity between images caused by seasonal and processing variations. Imagery was examined with naked eye and under magnification while features were being mapped. Several non-statistical comparisons were run to permit estimation of the degree of subjectivity involved in visual mapping from imagery. These tests involved analysis of the same image by several workers as described in our preliminary report (Erickson et al., 1975) and resulted in recognition that most interpretive study of ERTS imagery is quite subjective; that individual workers can to a degree standardize their interpretive techniques with practice; that no two workers can standardize these techniques between each other to produce consistently similar interpretations; and that variations in the quality and season of the imagery across the area seriously limits one's ability to repeat an interpretation from image to image across the entire area.

Maps of linear and tonal (for single images) features were produced first upon clear acetate overlays by using waxed pencils or acetate mapping ink (Berol Turquoise drawing ink for film). These were assembled into mosaics of the entire region in order to produce maps of the distribution of linear features in the Williston Basin. This procedure led to recognition of discrepancies in registration and scale of the images themselves. Variations are significant enough to cause question of the exact geographic relationships of features so mapped. This inexactness became a critical problem when the interpretive phase of the work was undertaken because ERTS-mapped features could not accurately be correlated geographically with features taken from various types of published geologic maps. Mapping was

therefore restricted to single images for tonal analysis and for other interpretive efforts.

A project of the type undertaken by us relies very heavily upon consistency of image quality, scale, and uniformity of processing technique for reproducibility of results within the study area. Likewise, the application of our results to other regions requires similar control throughout the ERTS program. We have discussed variations in quality of imagery in our preliminary report (Erickson, et al., 1975), and our opinions have not altered from those we expressed in that document. The problem of scale variation between images limited our ability to make geographic comparisons between features seen on ERTS imagery and those appearing on published maps.

GEOLOGIC SETTING OF THE WILLISTON BASIN

The Williston Basin is a sedimentary basin which occupies most of North Dakota. It extends into northern South Dakota, eastern Montana and southern Manitoba and Saskatchewan, Canada as outlined in Figure 1. Rocks in the basin record deposition during all Phanerozoic time periods and unconformities mark the sequence boundaries (Carlson and Anderson, 1965). During deposition the depocenter of the basin has shifted within the area of northwestern North Dakota, northeastern Montana, and southern Saskatchewan (Ballard, 1963). Carbonate deposition with attendant evaporites dominated during the Paleozoic with a gradual shift to clastics occurring during the Pennsylvanian and continuing to the Pleistocene. A bedrock map is presented in Figure 2.

Most of the region was glaciated during the Pleistocene, although major thicknesses of glacial sediment now cover only the northern two-thirds of the region, the result of Wisconsinan ice advance (fig. 3). The present course of the Missouri River through North Dakota approximately marks this boundary. The pre-Pleistocene courses of the Missouri drainage have been described by Bluemle (1972). Bluemle (1971) has also described the bedrock topography of North Dakota.

The Williston Basin is usually assumed to be a structurally simple, bowl-shaped feature, an opinion most recently stated by Sawatzky (1975). Three major structures, the Cedar Creek, Nesson, and Antelope Anticlines, and several lesser features (fig. 4 and fig. 5) have been defined within the basin. In addition the Weldon-Brocton-Froid Fault Zone (lineament) has been defined (see Dow, 1974) and recognized both surficially and in the subsurface. A lineament marking the Cedar Creek Anticline has been hypothesized (Erickson, 1970a) but to our knowledge the trace of this feature has not been precisely located in the field. Numerous subtle structural features have been described during the past twenty-five years as summarized by Erickson (1970a).

Petroleum production in the basin is not restricted to the major anticlines although each has provided a significant percentage of the hydrocarbon recovery from the region as shown in Figure 6. Reservoir-source rock relationships are complex. Fractures associated with faulting provide the major avenues of hydrocarbon migration into carbonate (usually) reservoirs and evaporites serve as major permeability barriers above the reservoirs. Source rocks have been well defined (Williams, 1974) and control of

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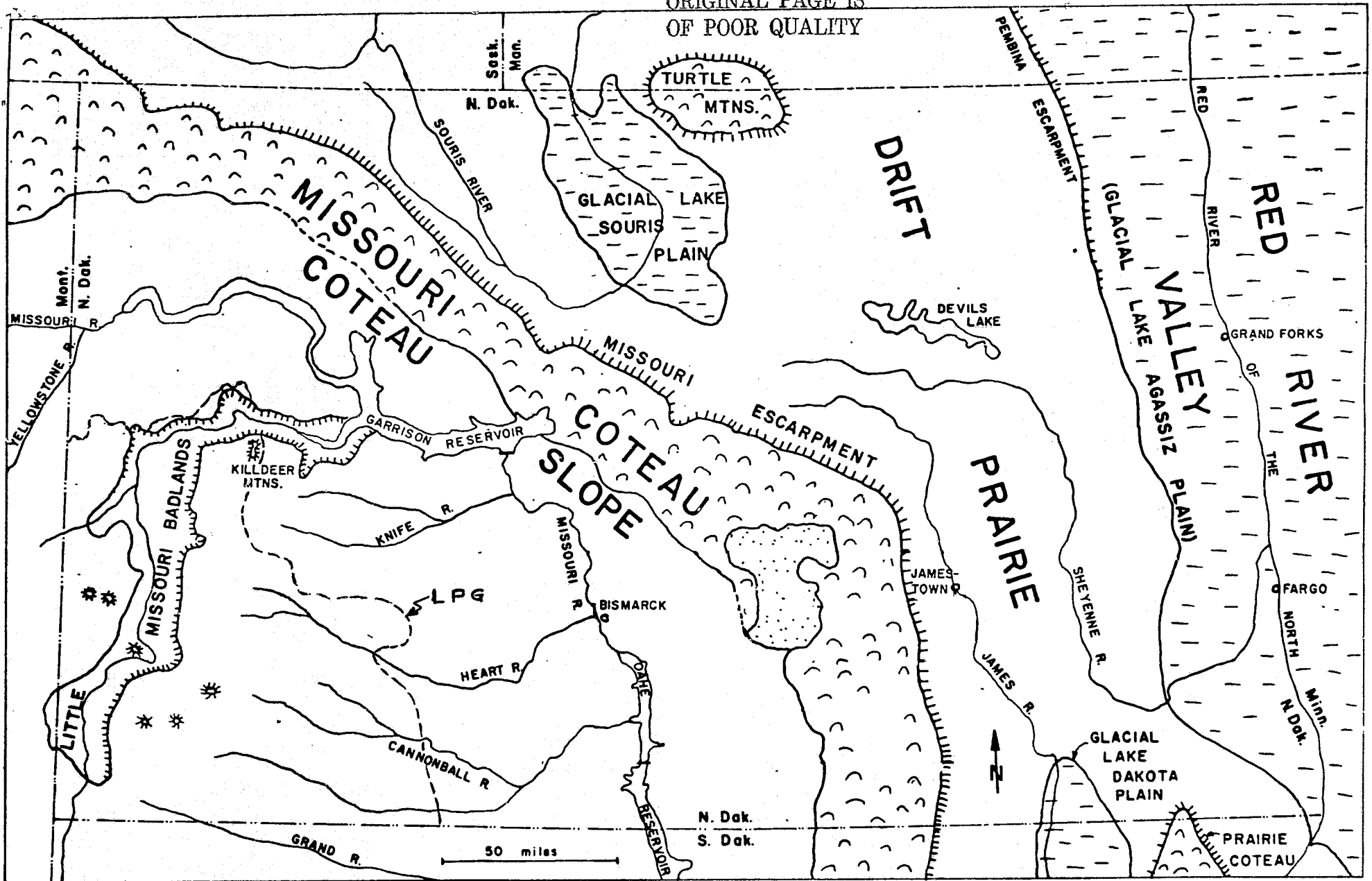


Figure 3. Physiographic map showing major glacial features of North Dakota. "LPG" indicates Limit of Pleistocene Glaciation (modified from Clayton and Freers, 1967).

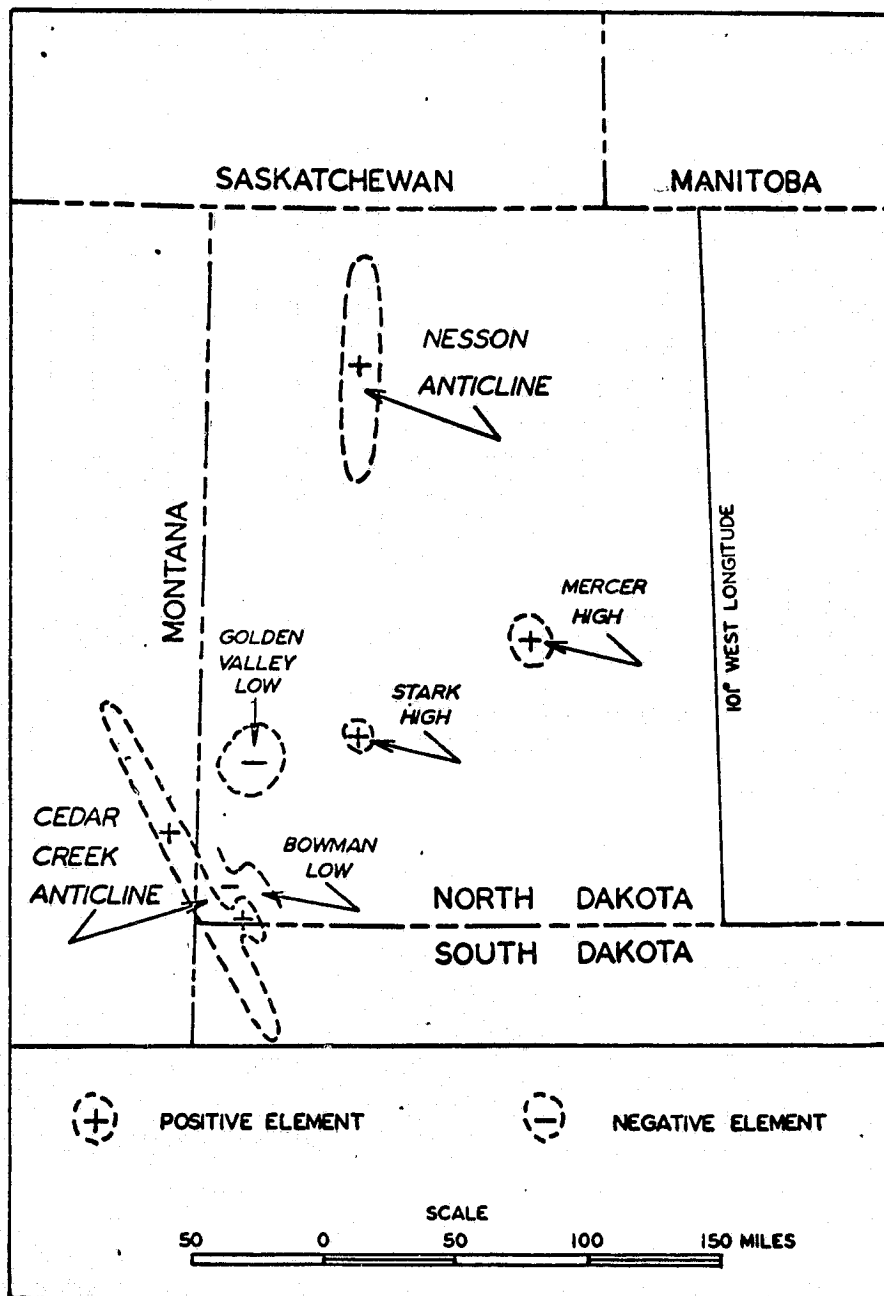


Figure 4. Sketch map of western half of North Dakota showing known subsurface structural features (from Dow, 1967).

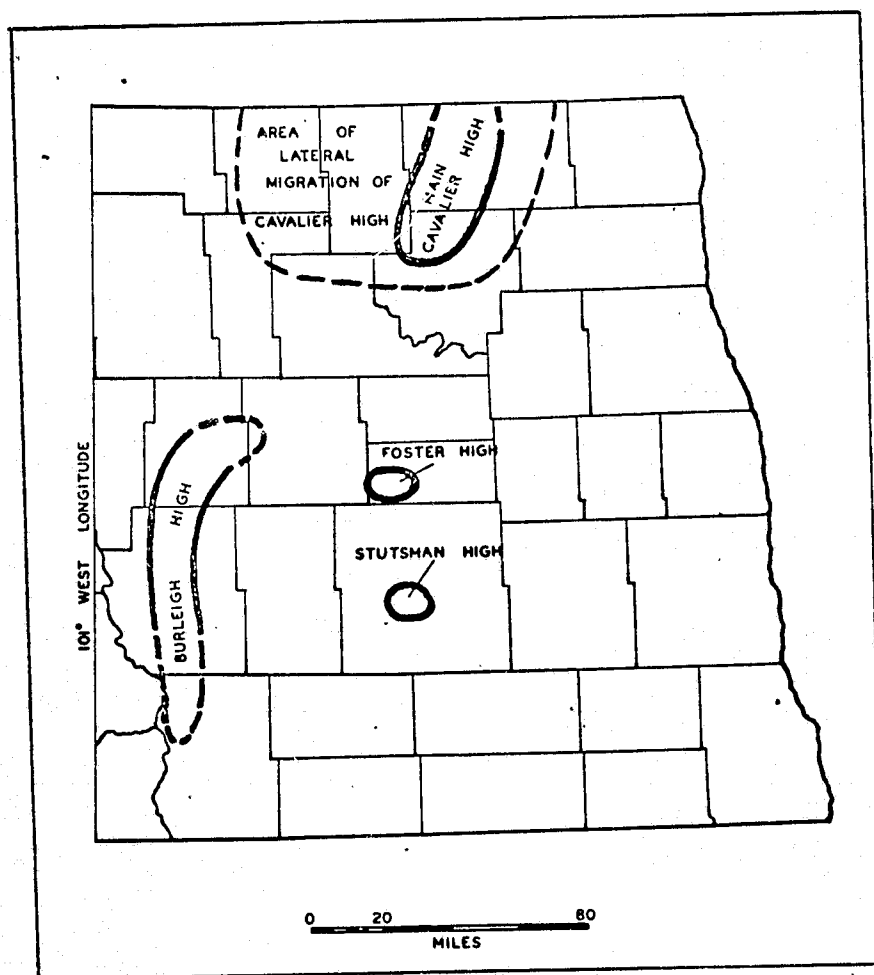


Figure 5. Sketch map of eastern half of North Dakota showing known subsurface structural features (from Ballard, 1963).

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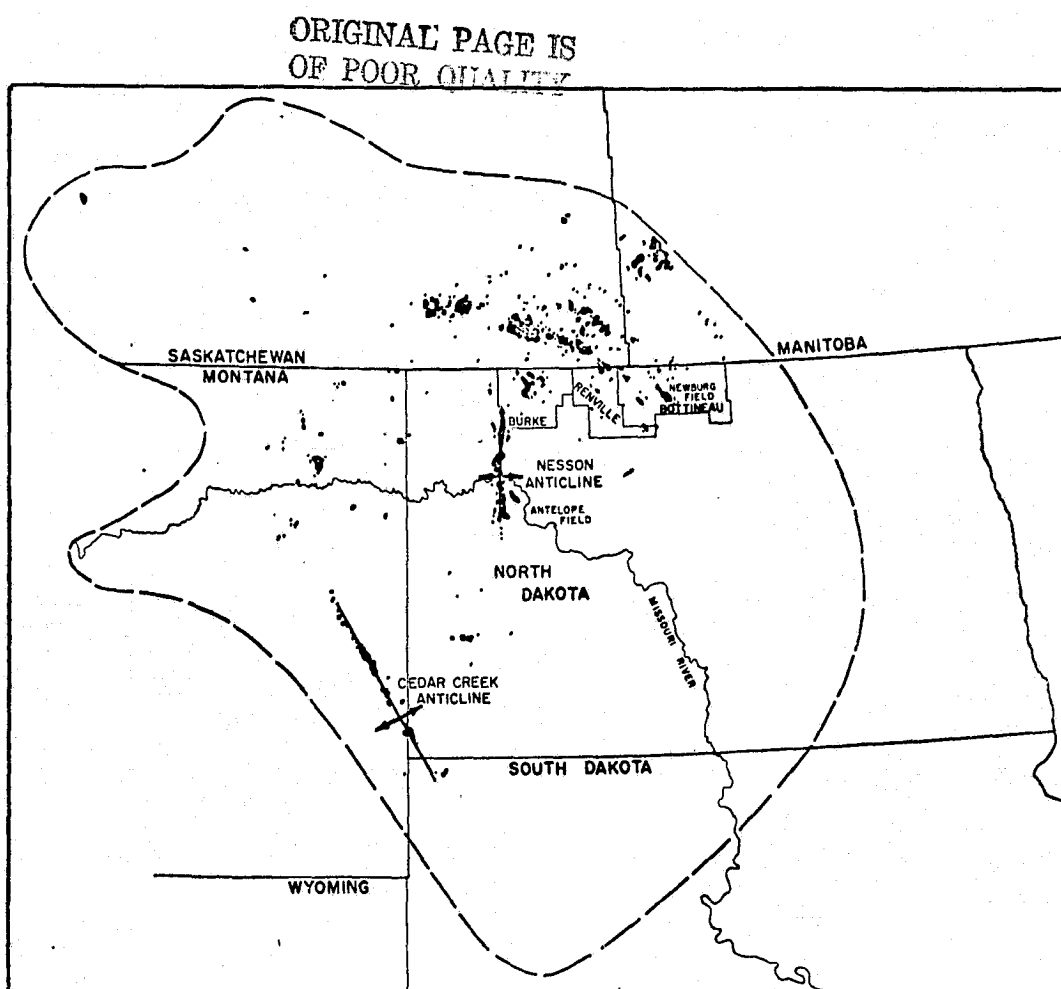


Figure 6. Location of hydrocarbon producing fields in Williston Basin (From Carlson and Anderson, 1965).

regional migration patterns has been thoroughly discussed by Dow (1974). Although the Williston Basin has been heavily prospected, much of that exploration has been conducted under the supposition that the region is structurally simple (which it is at the surface) and therefore that facies and stratigraphic traps rather than structural traps should receive the most attention.

TERMINOLOGY

Terminology available to describe features seen on ERTS imagery is not yet standardized and usage is not consistent. It is, in fact, difficult to verbally express many of the subtle nuances which appear on the images, particularly when their origins are not as yet understood. Tonal variations make up a large body of observations for which we have no adequate descriptive vocabulary. Frequently isolated tonal patterns have been referred to as "tonal anomalies" (Collins, et al., 1974), a couplet which infers that such features are indeed anomalous thus further implying that there is an understanding of what is normal or not anomalous. Such understanding is seldom the case and herein we shall attempt to employ other terms for these patterns. Tonal areas are places on the imagery where a variation in tonal quality occurs within a region of more or less uniform tone. Thus, a tonal area may be either lighter or darker, slightly more or slightly less mottled, somewhat more or somewhat less grainy than the surrounding region. The tonal change may be abrupt and straight, therefore appearing as a linear; or it may be a subtle transition having boundaries that are difficult to delineate. In reference to tonal

variations we will use interchangeably the words: tonal areas; tonal patterns; tonal features.

Terrain which appears "hazy" (in the sense of Collins, et al., 1974) will be referred to as a "hazy area", again in an attempt to avoid the word "anomaly". Also, as with tonal variations, when referring to hazy areas we will use interchangeably the words: hazy patterns; hazy features; hazy regions.

Lineations on the imagery are here termed "linears". They are shown in many ways, the most common of which are straight segments of streams, alignment of lakes, sharp boundaries between tones, linear patterns of land use, and obvious contacts between geologic units. The term "lineament" is used here to identify linear features which are proposed to result from structural disturbances in the subsurface and, by extension, the term refers to that structural element or zone (usually fault-generated) causing the linear pattern on the images. This usage is generally in keeping with the terminology proposed by Hoppin (1974). Unusual terms will be defined at the point of their use.

LINEAR FEATURES AND LINEAMENTS

Linear features were mapped for this study by O'Brien and Munsell using band 5 and band 7 imagery. Although each employed the same definition of a "linear feature", varying degrees of conservatism in mapping, coupled with differences in degree of glacial cover in the two portions of the basin (arbitrarily divided at lat. 47°N., combined to produce quite

different results. The following summaries for each region are largely derived from their reports.

Williston Basin North of Lat. 47°N.

Rectilinears and curvilinears were mapped according to four categories; (1) tonal boundaries, (2) tonal lines, (3) stream segments, and (4) elongate lakes. Tonal boundaries are demarcation lines between regions of differing tones, whereas tonal lines are discrete light or dark lines seen on a background of uniform tone. Linears are keyed according to the above categories in Figures 7, 8, 9, and 10.

In this region all four categories of linear features were seen in greater numbers on band 7 imagery. Few of the same rectilinear features appear on both bands 5 and 7, whereas the same curvilinear features frequently appear on both bands.

Comparison of distributions between glaciated (Wisconsinan) and non-glaciated terrain revealed that rectilinears and curvilinears are more frequently seen in the glaciated area particularly associated with terminal moraine complexes. Tonal lines and boundaries occur throughout the glaciated region. The non-glaciated region is dominated by rectilinears representing straight stream segments whereas tonal lines are much less common. This area also presents significantly fewer curvilinears.

As indicated by the rose diagrams on Figure 11, two directional trends are present among rectilinears: one oriented northwest-southeast; the other directed northeast-southwest. These trends coincide with those previously defined by Sproule (1962), who outlined a tectonic province

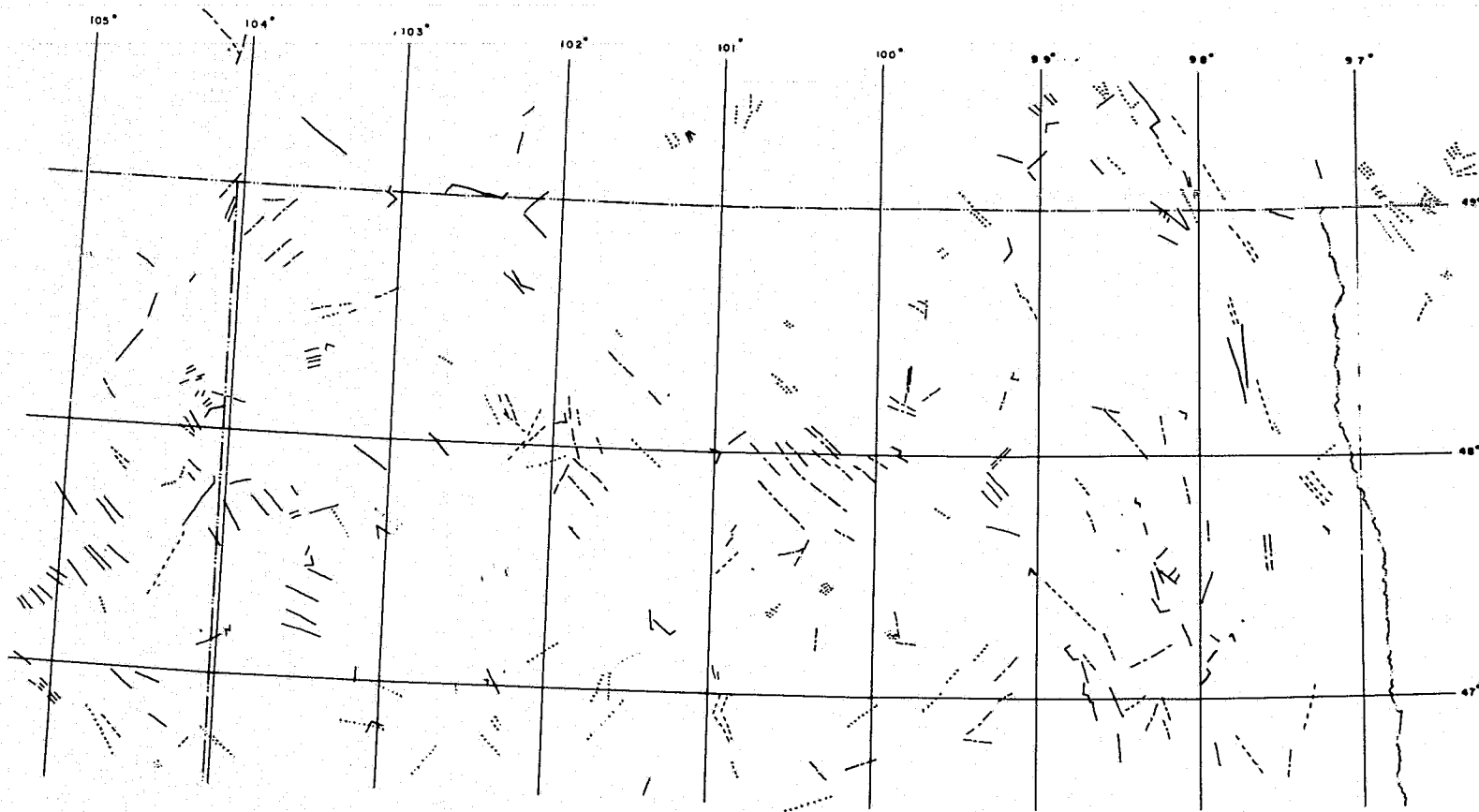
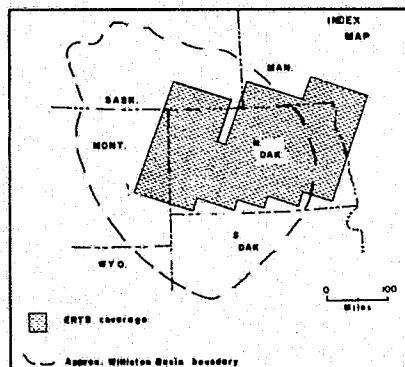


Figure 7. DISTRIBUTION OF
RECTILINEARS
ON
BAND 7 IMAGERY
(north of lat. 47°N)



Legend

- Tonal lines
- Tonal boundaries
- Stream segments
- Elongate lakes

APPROX SCALE 1:1,000,000

0 50
MILES

CJM

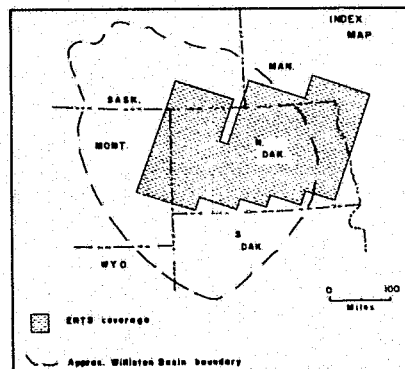
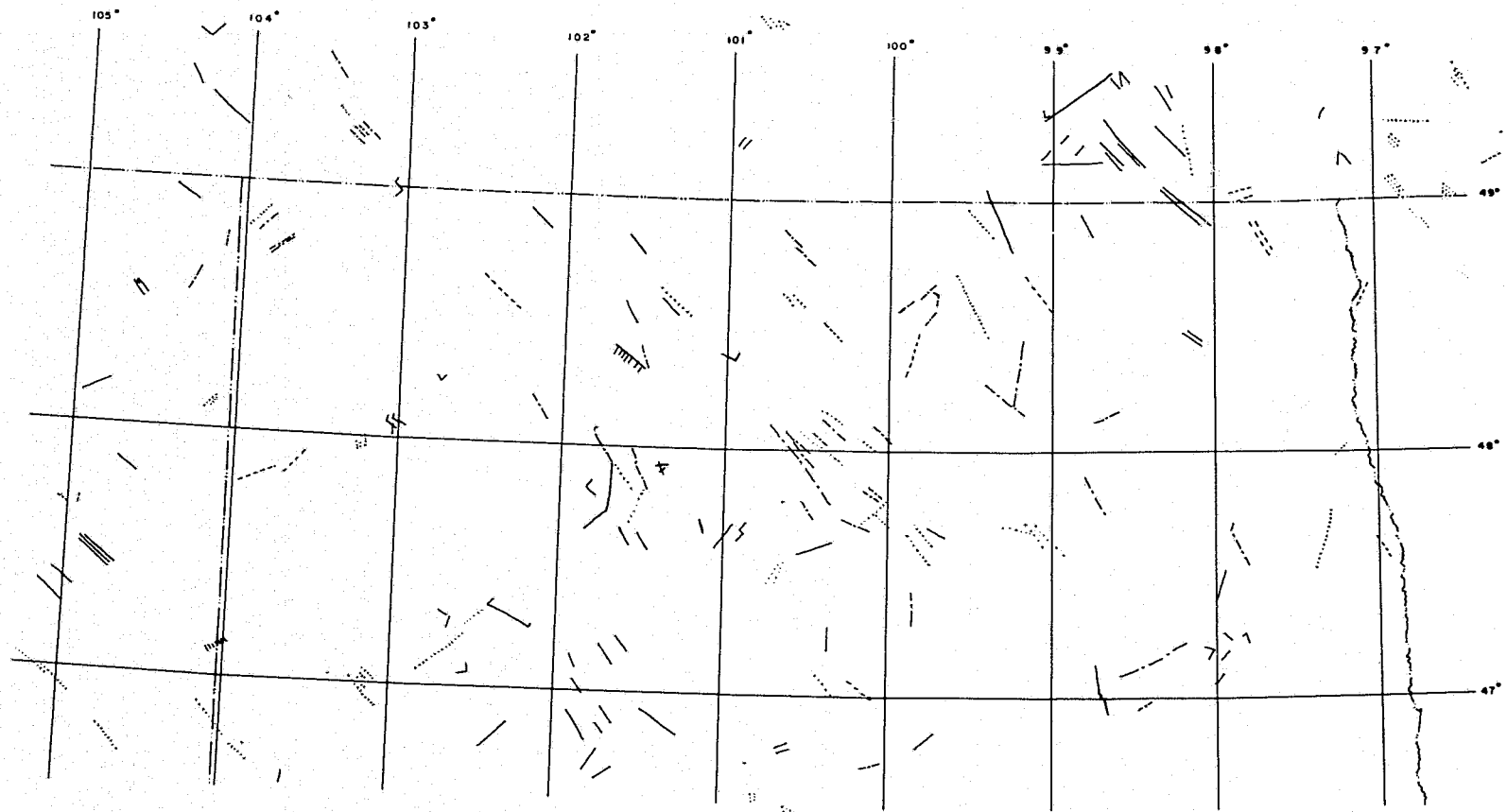


Figure 8. DISTRIBUTION OF
RECTILINEARS
ON
BAND 5 IMAGERY
(north of lat. 47°N)

Legend

- Tonal lines
- Tonal boundaries
- Stream segments
- Elongate lakes

APPROX SCALE 1:1000000
0 50
MILES

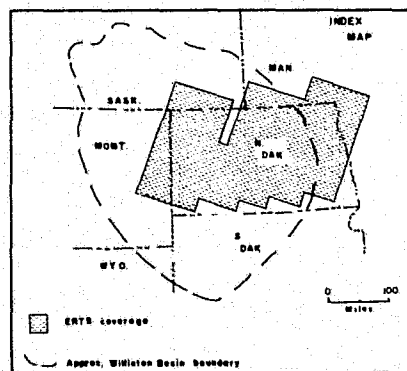
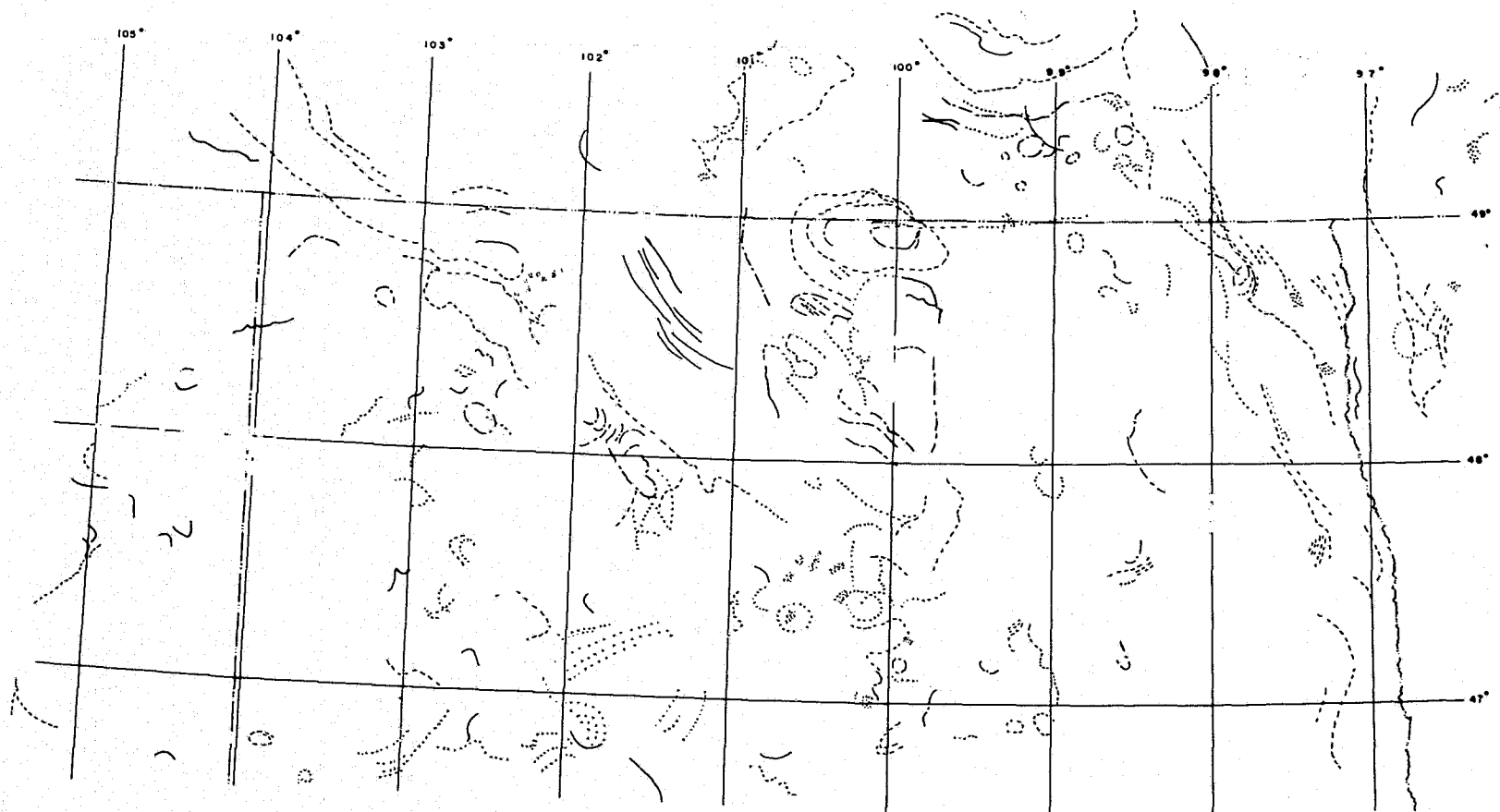


Figure 9. DISTRIBUTION OF
CURVILINEARS
ON
BAND 7 IMAGERY
(north of lat. 47°N)

Legend

- Tonal lines
- Tonal boundaries
- Stream segments
- Elongate lakes

APPROX SCALE 1:100,000
0 50
MILES

CJM

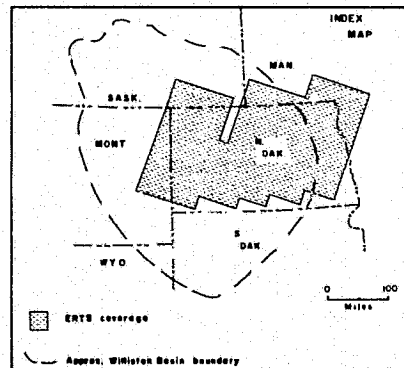
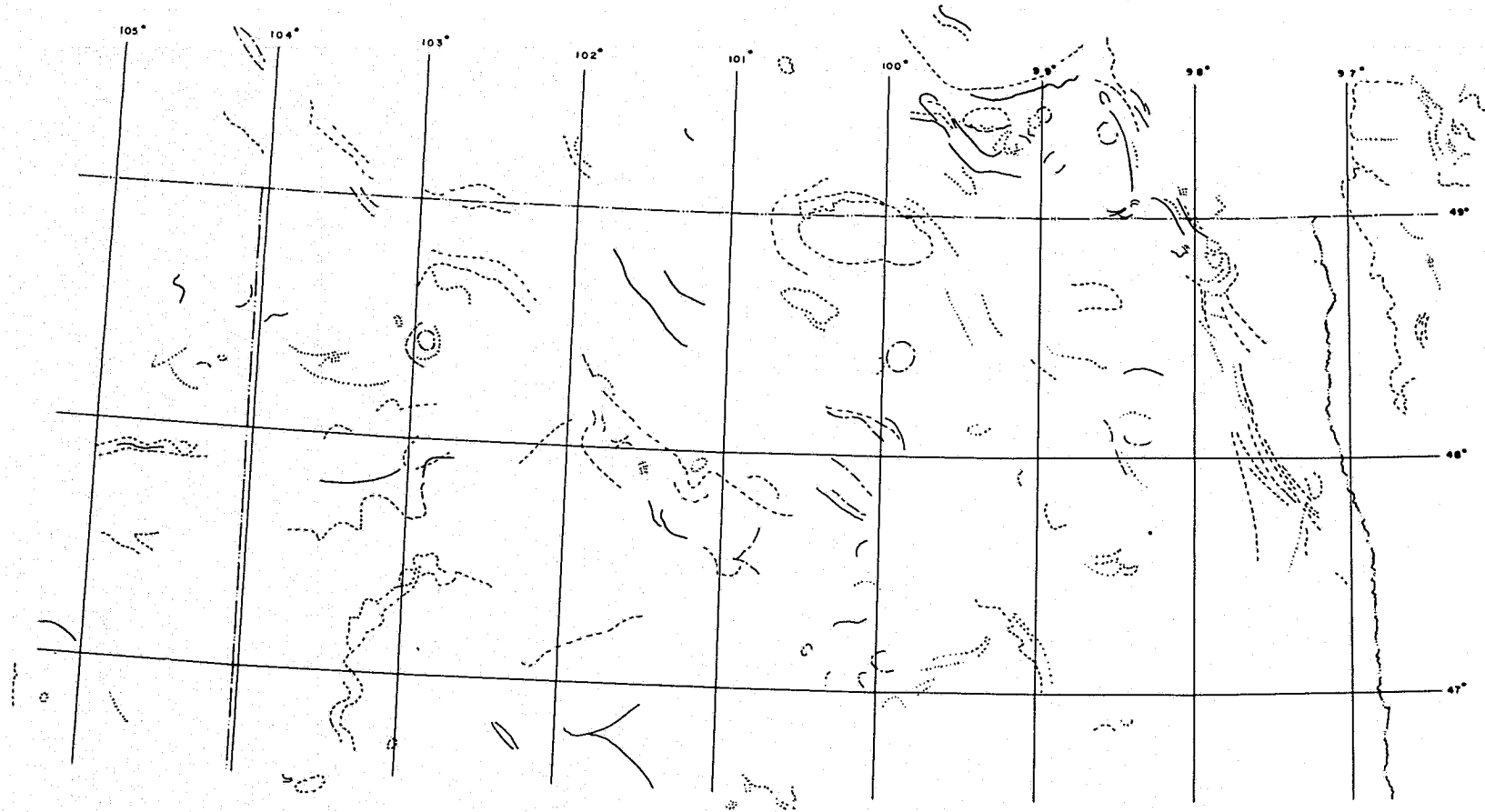


Figure 10. DISTRIBUTION OF
CURVILINEARS
ON
BAND 5 IMAGERY
(north of lat. 47°N)

Legend

- Tonal lines
- Tonal boundaries
- Stream segments
- Elongate lakes

APPROX. SCALE 1:1,000,000

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MILES

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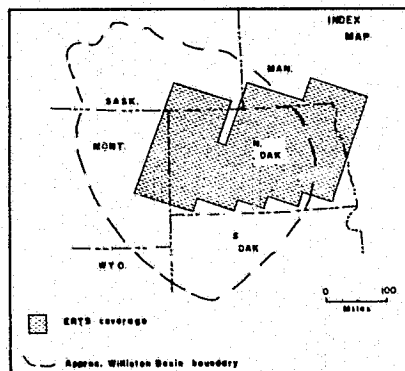
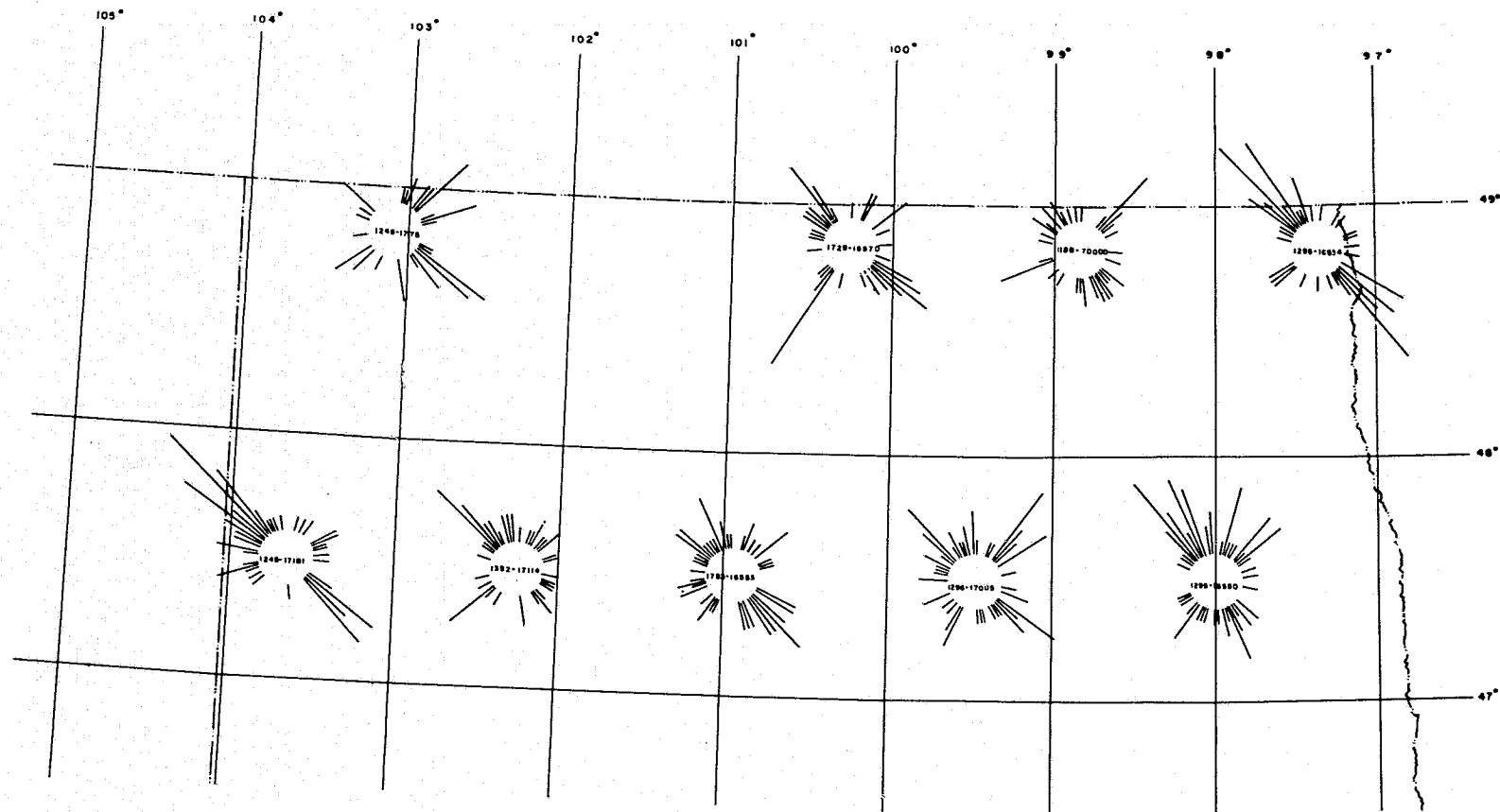
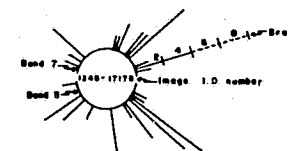


Figure 11.
ROSE DIAGRAMS OF
RECTILINEARS FROM
BANDS 5 & 7
(north of lat. 47°N)

Legend



APPROX SCALE 1:1000000

0 50 MILES

CJM

extending southwestward into the Williston Basin from northeastern Manitoba, and A.K. Erickson (1970a) who identified a group of northwest-southeast oriented "lineaments" based upon aerial photo interpretation and a synthesis of published geologic data. It is noted here that these Williston Basin trends parallel two of the four principal fracture directions in the Earth as proposed by Blanchet (1957).

Streams are the natural features which were most often mapped as rectilinears. This is not to suggest that streams are more often affected by whatever is causing the linears, but only that streams may exhibit the results readily. Variation in drainage pattern may result from structural control. Such variation takes place between the glaciated and non-glaciated portions of the basin. In the glaciated terrain drainage is dendritic, whereas streams in the non-glaciated region generally form a trellis-like pattern. Close examination of the streams in the dendritic drainage area reveals the presence of rectilinear stream segments, with strikes corresponding to those of streams in the non-glaciated area. This control of stream paths by fracture patterns exhibited in the non-glaciated area, is partially obliterated by glacial overburden, but its presence is demonstrated by the existence of rectilinear segments.

Several stream segments lie on lineaments mapped by Erickson (1970a). More specifically, those in the area of lat. 49°N. ; long. $98^{\circ}30'\text{W.}$ have the same azimuth direction and lie in close proximity to several unnamed linears in Cavalier and Pembina Counties, North Dakota. Another group located at lat. $47^{\circ}30'\text{N.}$; long. 104°W. (fig. 7) parallels the trend of the Bennie Pierre and Horsecreek Lineaments of Erickson.

An area of collapse moraine which extends southeastward from the northwest corner of the state is part of the Missouri Coteau (fig. 3). Lemke (1960), Erickson (1970a), and others have suggested that the Coteau, an elevated uneven surface of glacial origin, resulted from the deposition of till against a northeast facing fault scarp. Lemke (1960) submits that the Coteau scarp is structural in origin because the dip of preglacial beds is greatest near the escarpment and decreases northeastward away from it. Townsend (1950) described faulting and minor folding in the Fort Union Formation, Burke County, North Dakota, in the vicinity of the northern part of the Coteau. He concluded that the structural disturbance was of too large a scale to have resulted from ice shove and that it was most likely a reflection of subsurface tectonic activity. The present study does not confirm nor deny this possibility. Although glacial in origin the alignment of lakes and streams within the Coteau, parallel to the proposed faulting, may provide additional evidence for the structural origin of the Coteau scarp.

A concentration of rectilinears at lat. 47°N. ; long. $101^{\circ}40'\text{W.}$ (fig. 8) occurs in the vicinity of the Watford City and Williston Lineaments (Erickson, 1970a) and has a strike parallel to them. Tonal lines there exhibit a northeastward trend. They may mark an extension of Sproule's (1962) trend, or this concentration may be related to the earthquake center reported at Hebron, North Dakota (Erickson, 1970a). Another concentration of linears trending toward the northeast is located in Divide County in the northwestern corner of the state. This series of rectilinears, which might be termed en echelon, is probably a manifestation of the Weldon-Brockton-Froid Fault.

Two regions exhibit linear features which cannot be readily compared with known features. Just east of the Nesson and Antelope Anticlines at lat. 48°N. ; long. 102°W. (fig. 7 and fig. 8) an interesting array of linears occurs. Each of the four categories of linears is present having well developed northwestward and northeastward trends. No structural lineaments nor any prominent glacial features have previously been noted in this area. Because this area does exhibit the two regional trends so well at the surface (fig. 11), investigation of subsurface structure may be warranted.

The second region lies between lat. $46^{\circ}30'\text{N.}$ and $47^{\circ}20'\text{N.}$; long. 99°W. and $100^{\circ}30'\text{W.}$ (fig. 7). There Sproule's trend is well developed, but again no known faults nor fractures having this trend have been mapped previously. Presence of the Pierre and Fox Hills Formations contact may suggest proximity to a past hinge of the basin as discussed by Ballard (1963). Linears lie very near to and parallel to this contact. Establishing proof of such hingement would be a valuable contribution to our understanding of the Williston Basin.

It is interesting that the above comparisons to known features can be made, yet no rectilinears occur over the Nesson and Antelope Anticlines (fig. 19 and fig. 22). Realizing that these anticlines are subsurface structures, and that their discovery was made through seismic surveys, it is feasible that they would have no surface reflection. However, if these structures had their origin in faulting of basement rocks as has been suggested, it is hard to understand why other features, such as the Cedar Creek Anticline, formed by similar mechanisms, have surface manifestations

but the Nesson and Antelope do not.

With this in mind, investigation of areas which are devoid of rectilinears might also prove profitable. Three such areas occur on both bands at lat. $48^{\circ}30'N.$; long. $98^{\circ}30'W.$, and lat. $49^{\circ}N.$; long. 100° and $101^{\circ}W.$ (fig. 7 and fig. 8). The first of these lies in an area covered by ground moraine and situated directly above the main Cavalier High (Ballard, 1963) (fig. 5), a major positive feature developed on the now buried Precambrian erosional surface. The second area, at lat. $49^{\circ}N.$; long. $100^{\circ}W.$, encompasses the Turtle Mountains. These mountains, which may have been formed by faulting on their western and southern sides (Lemke, 1960) are at present covered by collapse moraine. A Paleozoic bedrock high, possibly erosional in origin but unrelated to the deeper, Precambrian erosional surface, underlies the mountains (Bluemle, 1971). The third region, a few linears at lat. $49^{\circ}N.$; long. $101^{\circ}W.$, lies in the lake bed of glacial Lake Souris. Inconsistency in structural character between these three regions allows no common structural interpretation to be applied to areas devoid of linears.

Curvilinears are found to correspond most frequently to known glacial features. Tonal boundaries at lat. $48^{\circ}N.$; long. $97^{\circ}30'W.$ (fig. 9 and fig. 10) are traces of the beaches of glacial Lake Agassiz and the Pembina Escarpment (fig. 3). Those in the northwestern corner of the map represent the flood plain of the Des Lacs River. The elliptical feature at lat. $49^{\circ}N.$; long. $100^{\circ}W.$ is the Turtle Mountains. The three tonal boundaries outlining the mountains may correspond to bedding contacts between the Hell Creek, Tullock and Ludlow (combined), and Tongue River Formations of Cretaceous and Tertiary age.

Many closed circular features outlined by tonal lines correspond to deposits of stratified drift as mapped by Colton, Lemke, and Lindvall (1963).

Such circular features which cannot be related to known glacial features are assumed to be unmapped areas of stratified drift. The tonal line from lat. $48^{\circ}20'N.$; long. $101^{\circ}50'W.$, to lat. $47^{\circ}40'N.$; long. $100^{\circ}30'W.$ on Figures 9 and 10 marks the northeastern edge of the Missouri Coteau. Groupings of tonal lines like those at lat. $47^{\circ}30'N.$; long. $100^{\circ}30'W.$ on Figure 9 all represent "washboard moraine" topography (Colton, Lemke, and Lindvall, (1963). The cluster of linears at lat. $46^{\circ}50'N.$; long. $102^{\circ}W.$ (fig. 9) may in some way be related to the earthquake center at Hebron. Another set of tonal linears occurs between the Hebron earthquake center and the Mercer High (Dow, 1964). These correspond to a bedrock trench (Bluemle, 1971) which lies between the above mentioned features. Another set of curvilinears appears at lat. $40^{\circ}50'N.$; long. $103^{\circ}W.$ and may be a surficial expression of the Keene Dome situated at the southern end of the Nesson Anticline according to Lemke (1960). Large curvilinears only occur in the glaciated area, a fact which implies that they are controlled surficially.

Williston Basin South of Lat. $47^{\circ} N.$

To produce maps of the southern half of the Williston Basin the same set of images was mapped three times on both band 5 and band 7 imagery. As noted previously, different linears were observed on each band, but both bands illustrate about the same number and density of linear features. Fabric and orientations of linears are also comparable between bands 5 and 7.

Linears are poorly expressed in areas of cultivated crop land but are well expressed in cultivated areas in this the largely unglaciated portion

of the basin. In the glaciated region more linears are seen in areas overlain by stagnation or ice-collapse moraine than in areas overlain by ground moraine because of the high numbers of sloughs ("potholes") and the non-integrated drainage associated with collapse moraine. With the exception of snow-covered winter imagery, linears were not strongly affected by seasonal change. Topographically expressed linears were significantly enhanced by light snow cover and low sun angle, an effect previously noted by Weir, et al., (1974).

Rectilinears for this portion of the basin are presented in Figure 12 (band 5) and Figure 13 (band 7). Rose diagrams of linears on each image mapped are presented on Figure 14 and are arranged by image center. As in the northern portion of the basin northwest-southeast and northeast-southwest orientations are most common suggesting a similar origin throughout the region.

Previous workers, including Russell (1929), Price (1944), Baker (1948), Flint (1955), Crandell (1958) and White (1961) have noted the preferred alignment of streams in a northwesterly direction and have attributed this to the prevailing northwest wind. This does not, however, explain the large number of non-stream linears having a northeasterly orientation. We feel it is more probable that the linears reflect two regional fracture or joint patterns of which the northwesterly set has been better developed.

Major structural features of the region such as the Black Hills Uplift, Sioux Uplift, Cedar Creek Anticline and the center of the Williston Basin appear to have had little affect in changing either orientation or distribution of linears. Possibly because all of these features generally have

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Figure 12. RECTILINEARS ON BAND 5, ERTS-1 IMAGERY (south of lat. 47°N)

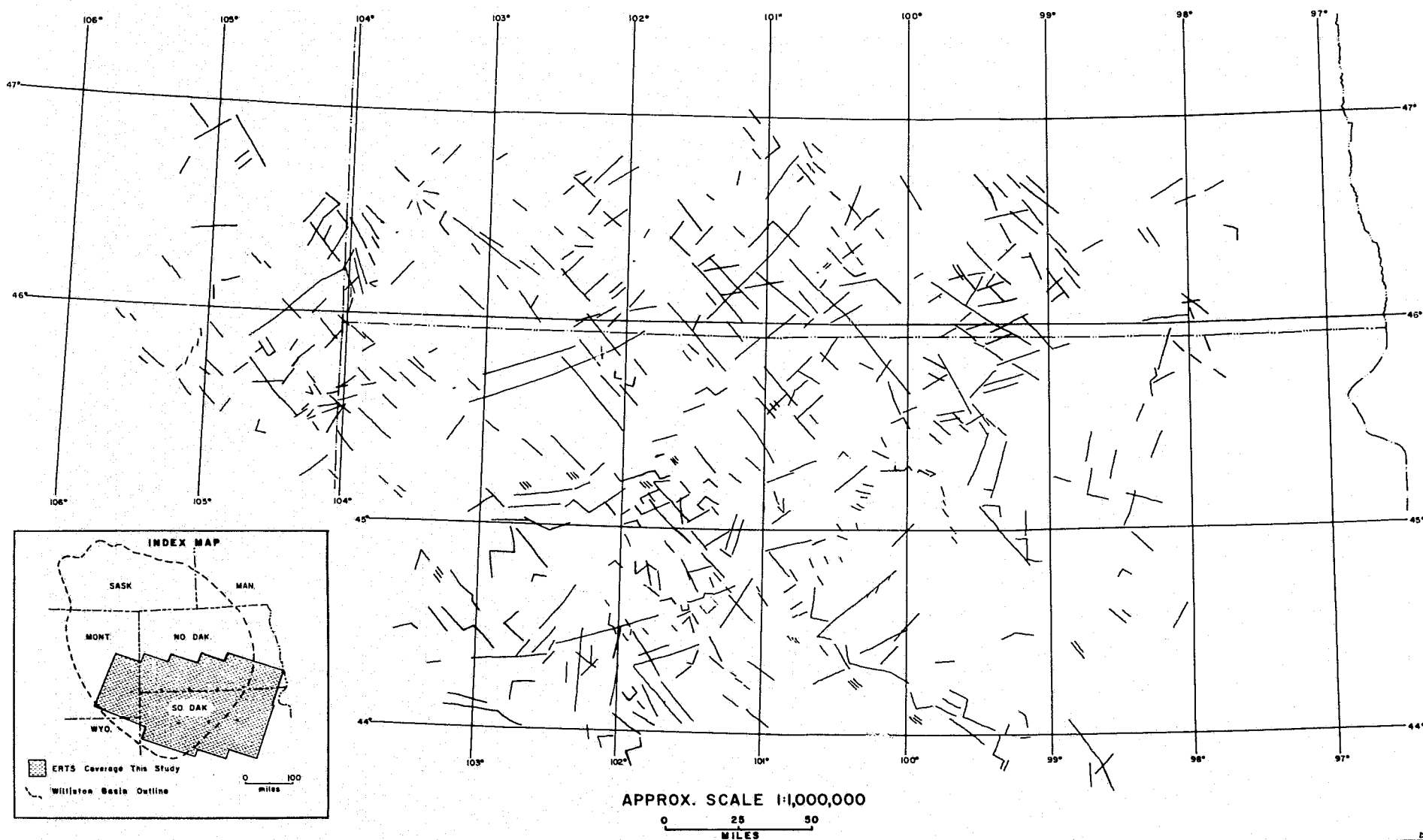


Figure 13. RECTILINEARS ON BAND 7, ERTS - I IMAGERY (south of lat. 47°N)

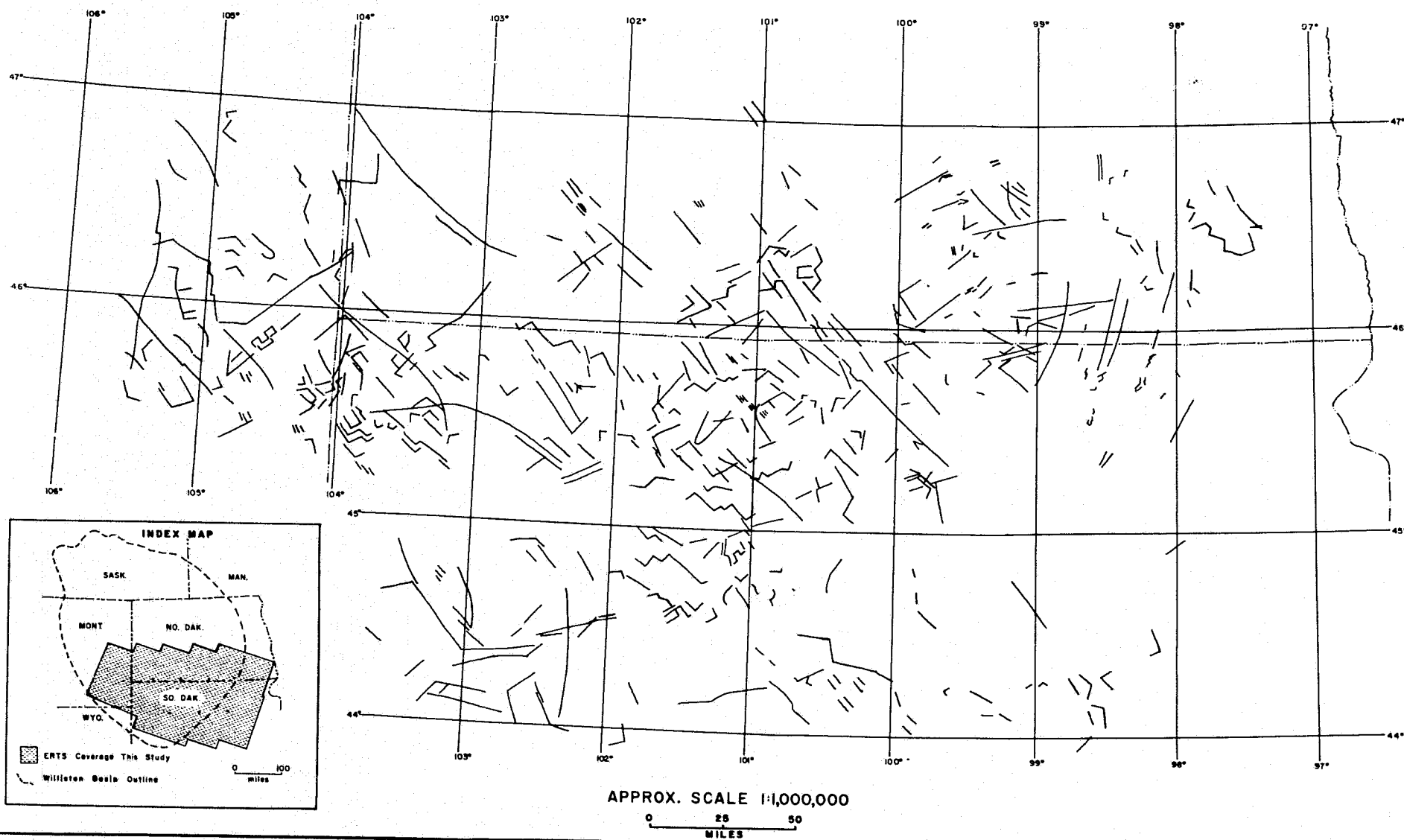
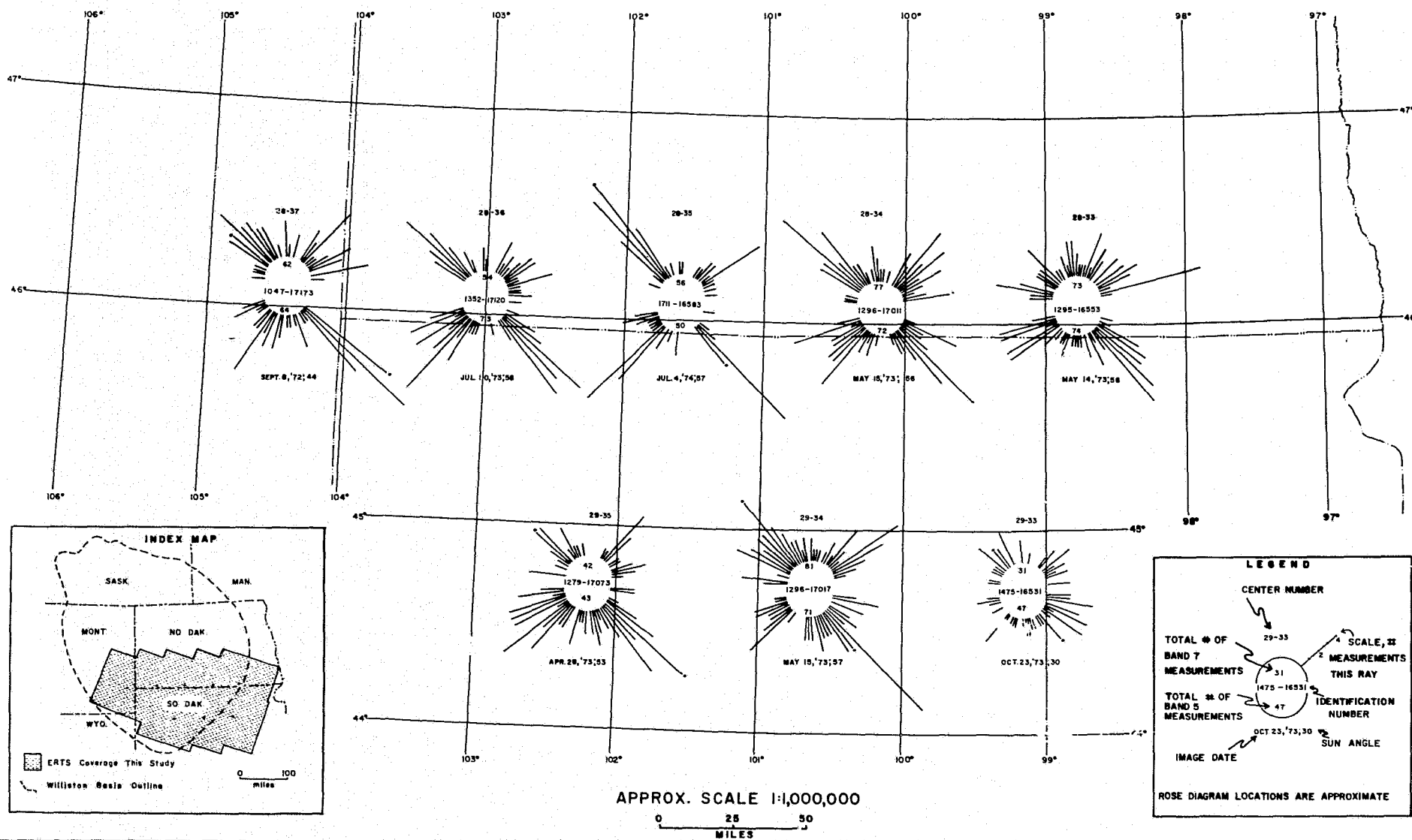


Figure 14. ROSE DIAGRAM OF RECTILINEARS, BANDS 5 & 7, ERTS-1 IMAGERY (south of lat. 47°N)



a northwest orientation they may only cause local variations which cannot be detected on rose diagrams of entire images. Consequently rose diagrams are better suited to determine regional trends rather than to call attention to any single structure.

Curvilinear features were defined according to the same categories mentioned previously. Those expressed as tonal borders were often indistinct and, on a mottled low-contrast print, it was often difficult to decide whether a high number of tonal changes, or no tonal changes were present.

Size of curvilinears varied considerably both in length and in radius of arc as may be seen on Figures 15 and 16. Large sweeping curves and short tight curves were observed. The short tight curves occur together as a mass on band 7 lat. 44°N. ; long. 99°W. , lat. 45°N. ; long. 98°W. , and lat. 46°N. ; long. 100°W. and on band 5 lat. $44^{\circ}30'\text{N.}$; long. $103^{\circ}30'\text{W.}$. No preferred direction of opening of curvilinears was observed. The smallest curvilinears are inferred to be meander scars because of their size, number, and association in river terraces. Larger curvilinears having unique width and tone are believed to be formed by either saline seep or dropping out of thin, light-colored lithologic units. This group of features no doubt encompasses many of the "geomorphic anomalies" as described by Collins, et al., (1974) in the Anadarko Basin of Oklahoma. It should be noted, however, that almost no curvilinears appeared on snow-covered imagery, an indication that they are not expressed topographically in most cases.

Figure 15. CURVILINEARS ON BAND 5, ERTS - 1 IMAGERY (south of lat. 47°N)

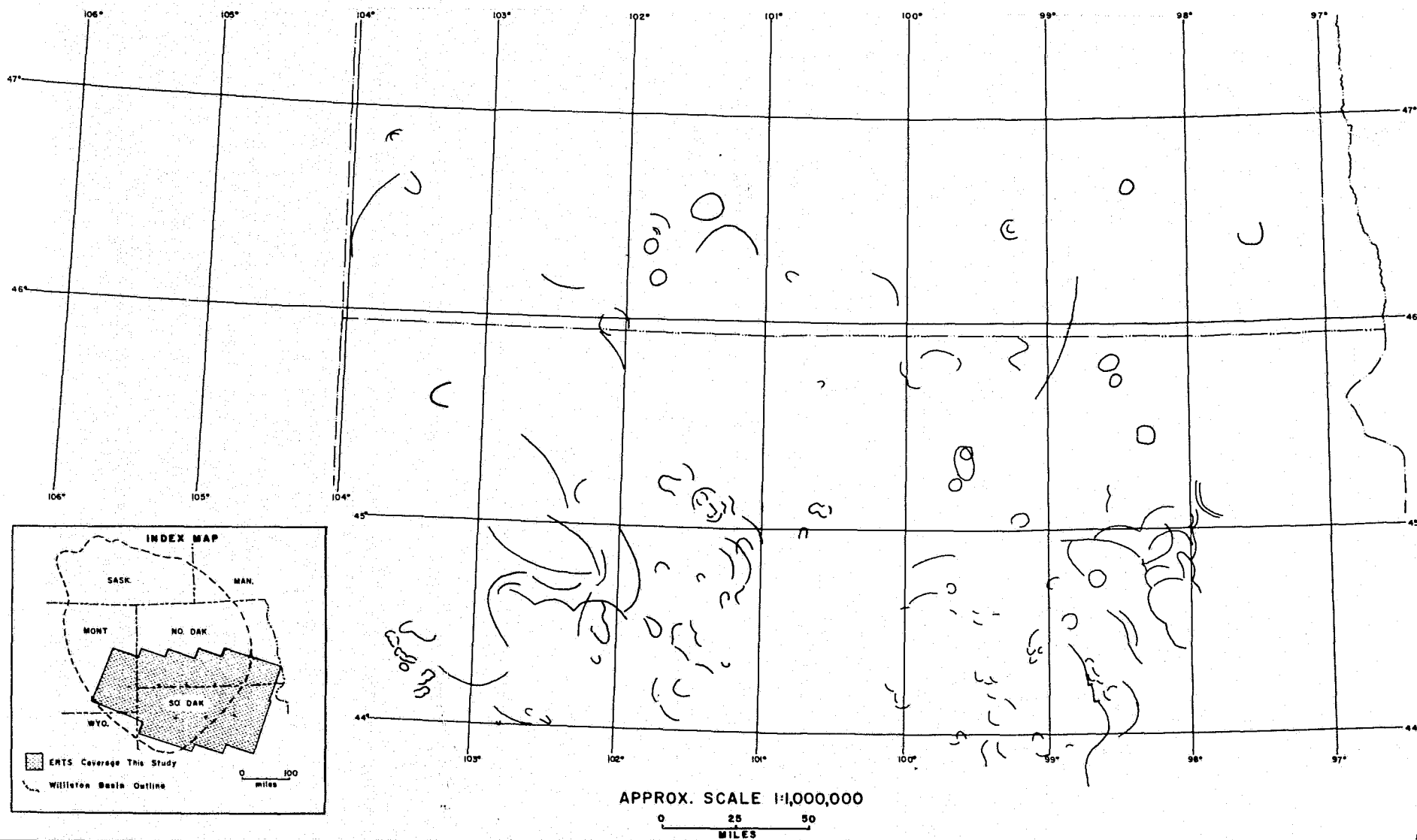
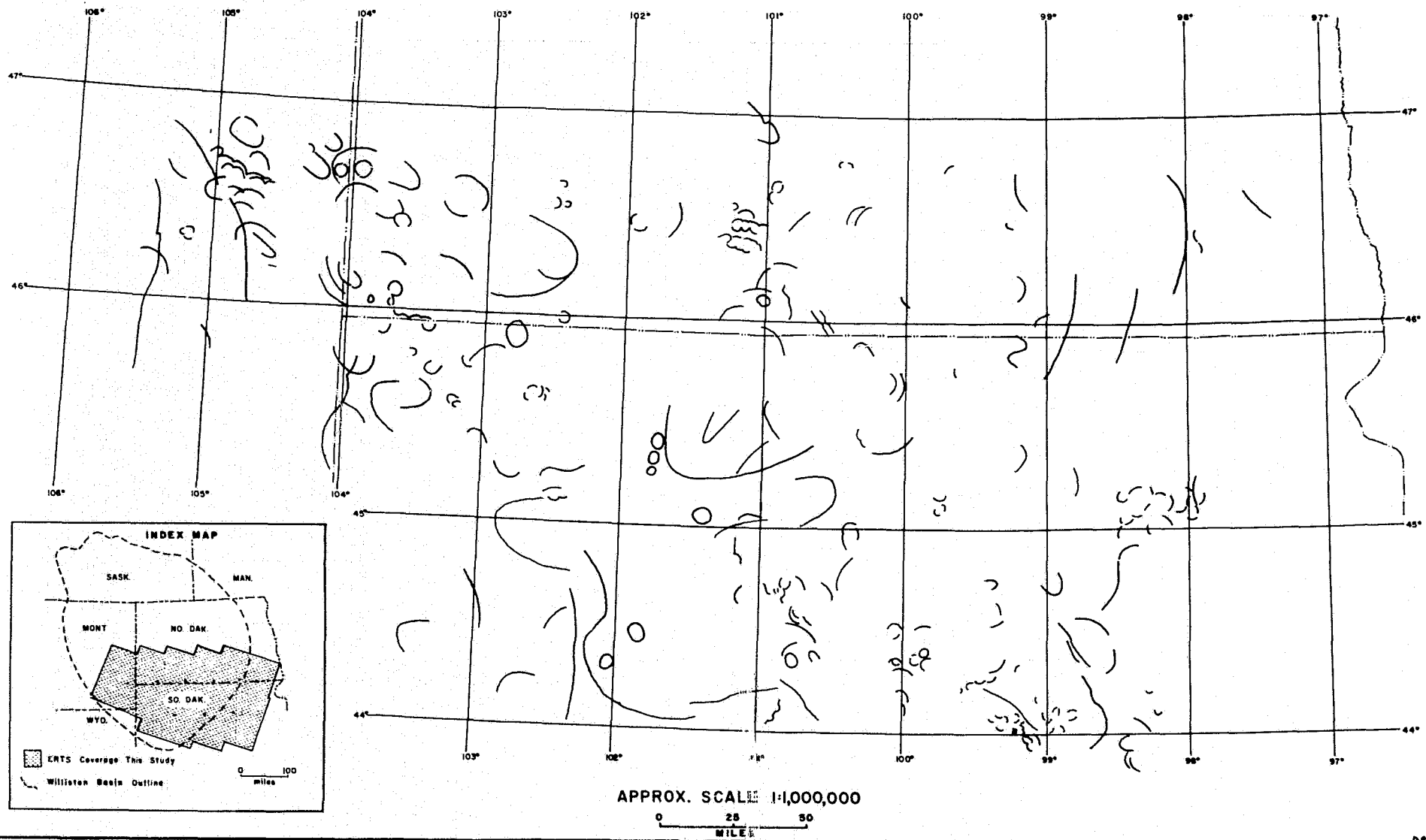


Figure 16. CURVILINEARS ON BAND 7, ERTS - I IMAGERY (south of lat. 47°N)



Comparison with Previous Studies

Prior to 1970 linears and structurally controlled lineaments were not considered to be significant to Williston Basin geology or to the entrapment of its contained hydrocarbons. This is unusual in view of the fact that studies of individual oil fields clearly demonstrated the importance of fracture patterns at depth to accumulations of petroleum (Folsom, et al., 1959; Dow, 1974). Faulting has been hypothesized as a controlling mechanism for the Cedar Creek (Gwynn, 1964; Davis and Hunt, 1956) and the Nesson and Antelope Anticlines (Bateman, 1957; Folsom, et al., 1959), the major positive structural features of the basin.

A study by A.K. Erickson (1970a) of linears seen on mosaics of aerial photographs at a scale of 1:1,000,000 provided the basis for the most thorough documentation of surficial linears to date in the North Dakota portion of the basin. A synthesis of previous studies of many types resulted in a map defining structurally-controlled lineaments plotted as they related to such features as earthquake epicenters, drainage patterns, subsurface stratigraphic data, magnetic anomalies, and surficial geology. The structural development of the Nesson and Antelope Anticlines (see fig. 17 and fig. 18) was described in detail by A.K. Erickson in 1970(b). His interpretations indicated that deep (8-10,000 ft.) structures created on the Precambrian surface by repeated activation of several northwestward trending shear zones were the cause of periodic draping of sedimentary rocks in the basin and, furthermore, that the shear zones responsible for movement of these crustal blocks were shown at the surface by linears. They were therefore mappable on aerial photos of the proper scale.

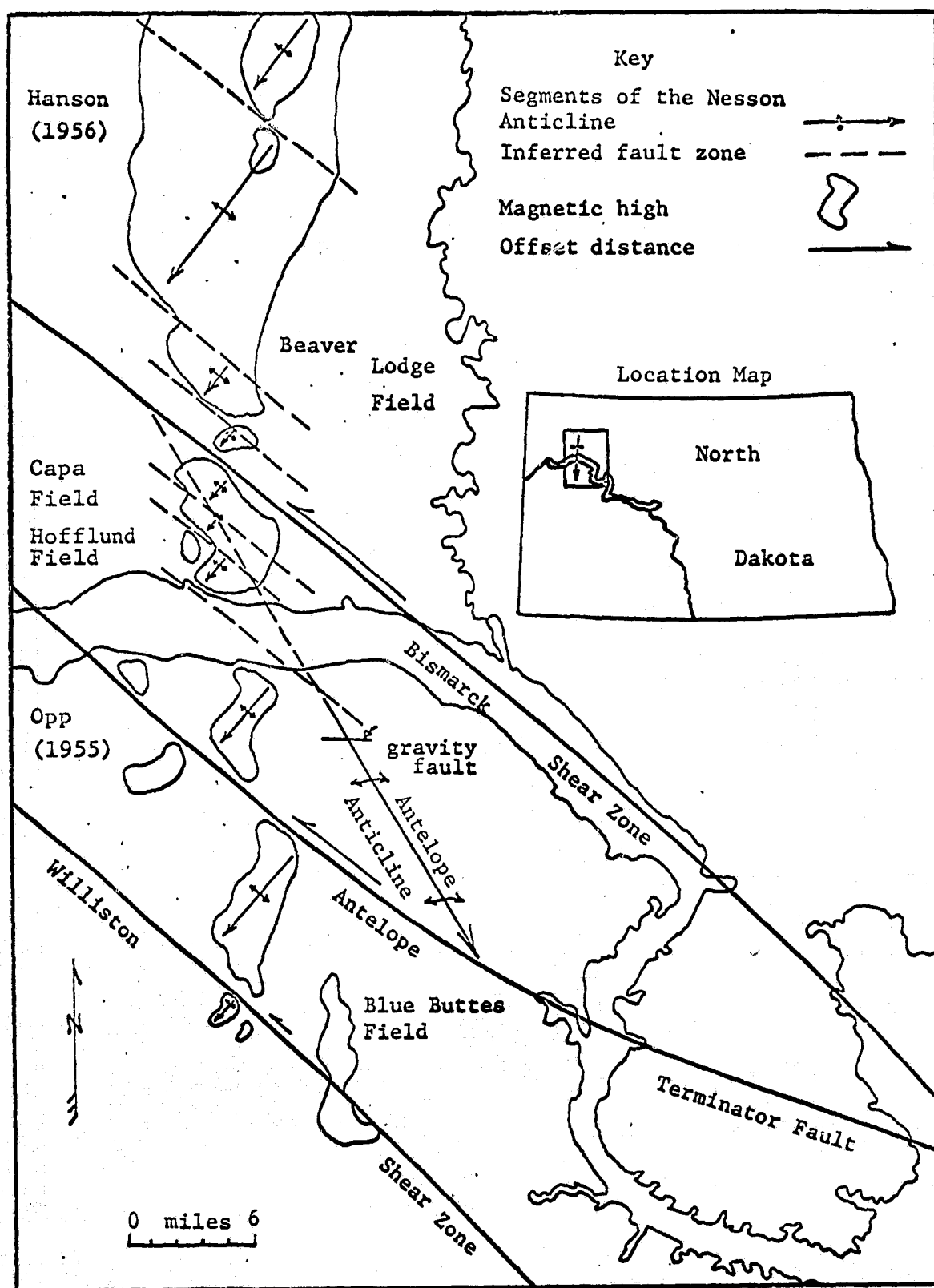
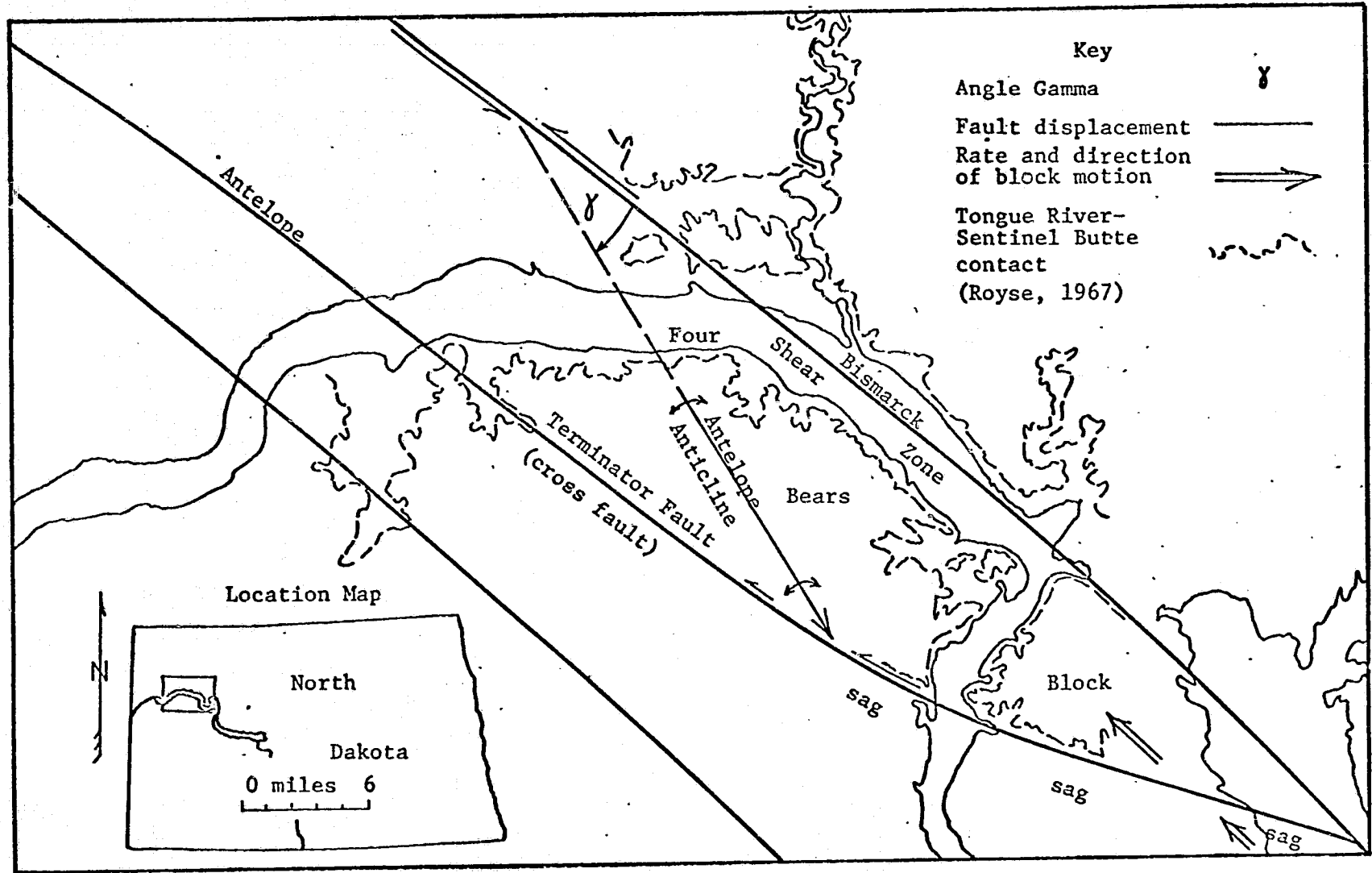


Figure 17. Sketch map of Nesson-Antelope area as interpreted by A.K. Erickson (1970a).

Figure 18. Detailed sketch map of Antelope area as interpreted by A.K. Erickson (1970a).



We have made a detailed comparison between Erickson's (1970a) work and our imagery and linears maps with the following conclusions:

- 1) The prevailing northeast and northwest trends of linears are substantiated by ERTS imagery.
- 2) A NW-SE lineament defining the western edge of the Cedar Creek Anticline is clearly visible on ERTS imagery (ID 1047-17173; fig. 26), probably seen in its entirety for the first time.
- 3) The Weldon-Brockton-Froid lineament can be defined though with less certainty (ID 1263-17181; fig. 24).
- 4) The Yellowstone, Bismarck, and Little Missouri lineaments are recognizable primarily as straight stream segments but are not clearly defined.
- 5) Other lineaments defined by A.K. Erickson are not recognized with any certainty and perhaps are masked among numerous linears having similar orientations.
- 6) Structural interpretations of the Nesson and Antelope Anticlines cannot be made from ERTS imagery nor can these subsurface structures be recognized on the imagery.
- 7) Numerous linears not defined by A.K. Erickson (compare fig. 25 to fig. 26), including NE trending cross-faults on the Cedar Creek Anticline can be mapped from ERTS (ID 1047-17173; fig. 26) but their significance to subsurface structure cannot be evaluated.

The above comparisons emphasize the need to examine features of the imagery other than linears. Detailed examination of ERTS images of the regions containing these structural elements will be presented below in descriptions of areas A through D.

TONAL AREAS

The array of tonal variations present on ERTS imagery is staggering. Every image in every band at each date of recording presents different

tones for evaluation. The area covered by our study was too broad to permit detailed mapping of tones; rather several studies were made using particular image centers as discussed below. Some general conclusions regarding tonal features can be made.

- 1) They share no common cause.
- 2) Most are not associated with purely topographic features.
- 3) Major structural features such as the Cedar Creek Anticline and the Turtle and Moose Mountains are readily seen as tonal patterns.
- 4) Some structural features known from subsurface studies but poorly understood in the field seem to be recognizable by tonal analysis. Examples include the "Linton Dome" (Laird and Towse, 1951, the southern tip of the Burleigh High (fig. 5) and the "Golden Valley Low" (Dow, 1964) shown on Figure 4.
- 5) Circular or elliptical tonal features are numerous. Their relationships to petroleum reservoirs are not clear. Although some oil fields seem to lie within such features, many others do not. Circular tonal features probably merit close attention during exploration. Relationships which we have considered will be discussed in the section entitled ERTS Examination of Williston Basin Producing Areas.
- 6) Because of the numerous variations in tone from one image to the next it is not possible to establish a particular "key" tone to search for across the entire basin. Such work is best restricted to single images.

HAZY AREAS

Attempts were made to seek out "hazy" areas as described by Collins, et al., (1974) in their study of Anadarko Basin imagery. In that work a close correlation between locations of "hazy anomalies" and known petroleum production was noted and the further documentation of their observations was originally described as a principle thrust of our study in hopes their technique could be applied in other geographic regions.

In keeping with recommendations made in the Eason Oil Company Report (1974) our search for hazy features concentrated on, but was not limited to, band 4 imagery. Numerous hazy areas were identified and many were mapped and presented in our preliminary report (Erickson, et al., 1975, Pl. 3). These features were carefully examined at that time, prior to our study of petroleum production sites in the region.

During the third phase of study, imagery of particular oil-producing areas was examined in detail for all types of features including "hazy anomalies." Our conclusions from that work are as follows:

1) Band 4 imagery frequently shows areas on which features are not easily resolved, are indistinct, or absent. We assume these are similar to the "hazy anomalies" described by Collins, et al., (1974).

2) Such areas are not consistently hazy from season to season or year to year and they seem to be more common on summer imagery.

3) Many oil fields lie near, and some lie within, hazy areas (fig. 21 and fig. 23). There does not seem to be a correlation between the two, and we feel it is likely that a random distribution of oil fields when overlain on a map of "hazies" could produce a similar spatial relationship, although this has not been statistically tested. We assume any association to be one of chance.

4) No one-to-one relationship exists between hazy areas and known petroleum fields.

5) We have concluded at present that hazy areas on band 4 imagery have resulted from some atmospheric phenomenon (assuming that they are not artifacts of the image making process, a position supported adamantly by Collins, et al., 1974)

ERTS-1 EXAMINATION OF WILLISTON BASIN PRODUCING AREAS

Four images covering most of the Williston Basin hydrocarbon-producing areas in North Dakota were examined in particular detail in both black and

white and in color. Attempts were made to relate features on the imagery to subsurface data in these regions. Structural features which are cited, distribution of oil fields, and approximate positions of the four detailed studies (areas A-D) are presented on Figure 19 modified from Dow (1974, fig. 1).

Area A - Bottineau Region

The area north of Minot in Bottineau and Renville Counties, North Dakota and northward into Saskatchewan, Canada, produces oil from Mississippian and some Triassic reservoirs. These pools are not associated with major structures but rather result from a variety of stratigraphic traps into which hydrocarbons have apparently migrated through regional fracture systems from source rocks (Bakken Shale-Devonian) to the southwest (Dow, 1974). Salt or anhydrite appear to be the capping units over many of these fields.

Analysis was made using image ID 1729-16570 with the following results (fig. 20 and fig. 21).

Linears:

- Not a major element of this region. Very few are recognized.
- Heavy glacial overprint may mask the regional fracture pattern.
- Shape of the Turtle Mountains may suggest fault control and Erickson (1970a) mapped it as such. Lineaments in his locations were not seen on ERTS imagery.

Tones:

- Wide variety of tones present particularly on bands 5, 6 and 7.
- Major tonal features can be directly related to known glacial features described by Lemke (1960).
- Very subtle circular and elliptical tonal areas are present.

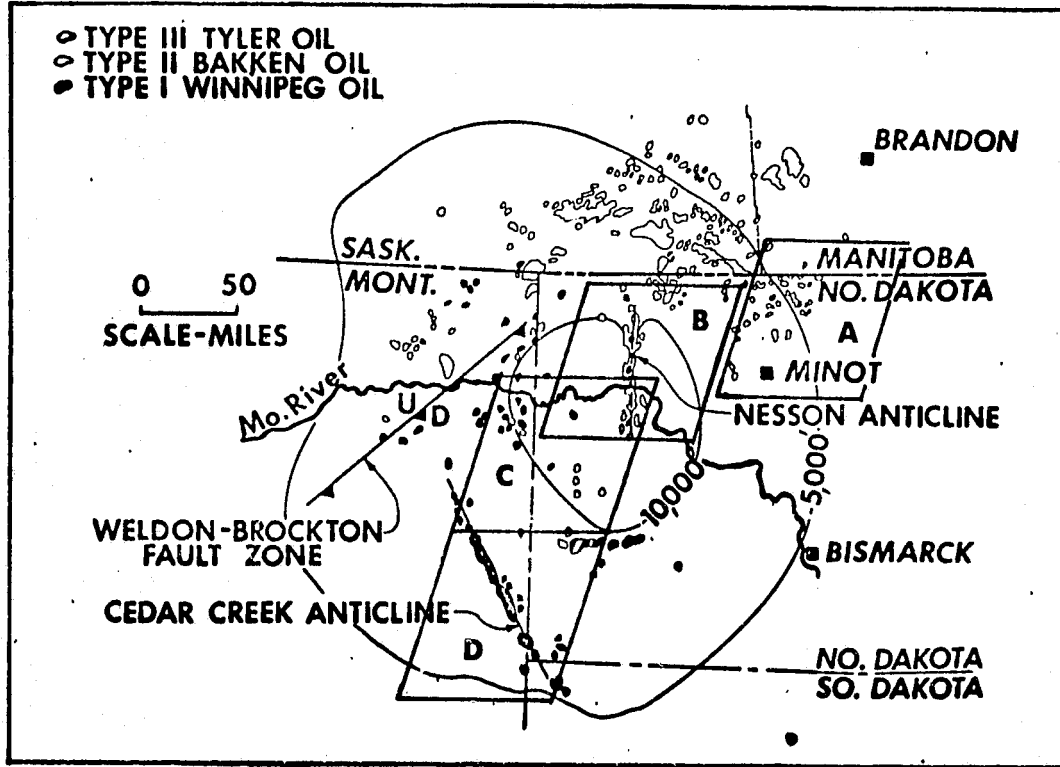


Figure 19. Location map for Areas A-D of detailed study (modified from Dow, 1974).



Figure 20. Composite map of Area A displaying linears and tonal features from all bands of image ID 1729-16570. Oil fields shown as solid closed lines.

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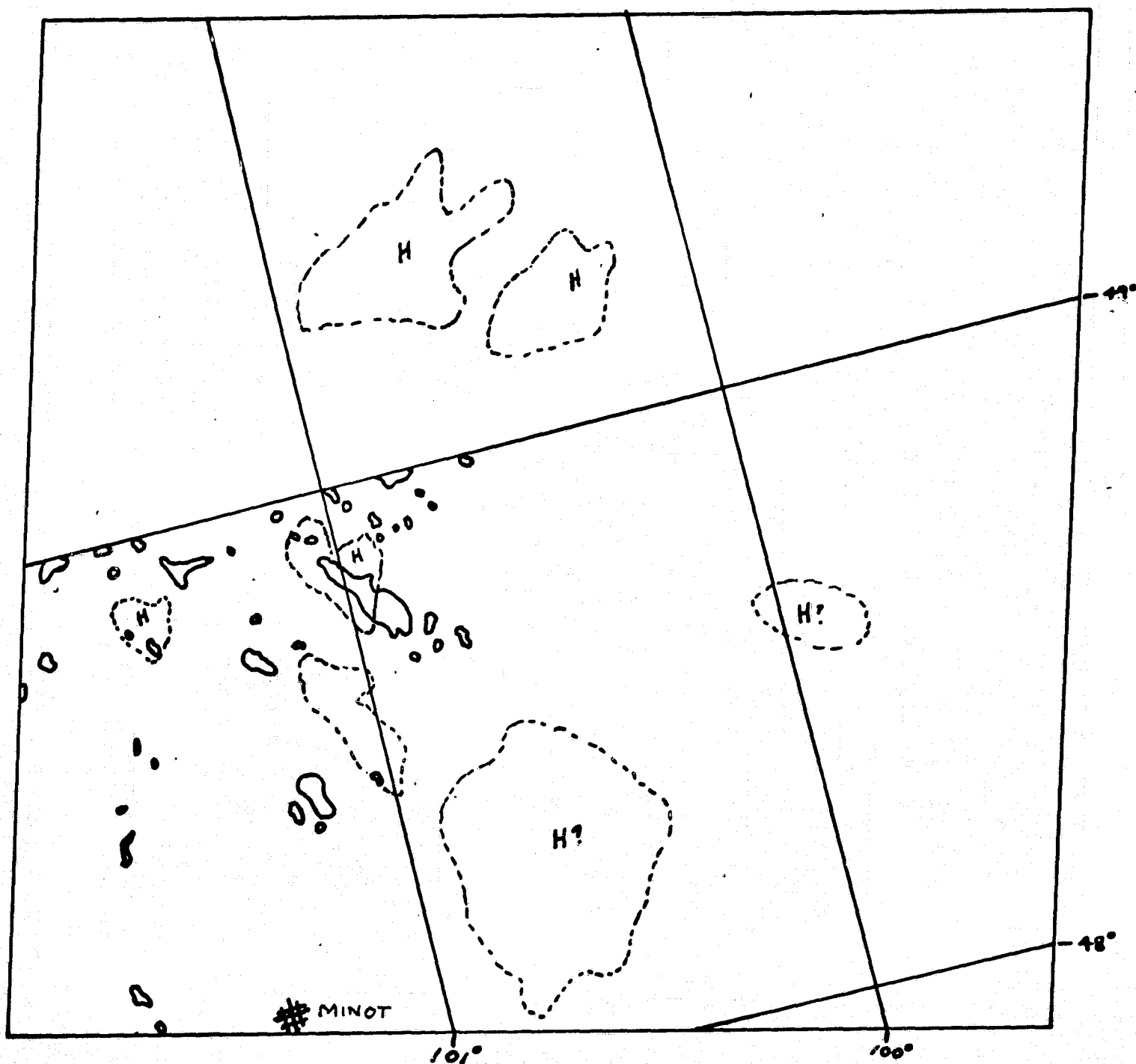


Figure 21. Map of Area A giving locations of hazy regions from band 4 of image ID 1729-16570.

- Much of the subsurface control in the area has been related to salt-solution collapse in the Devonian Prairie Evaporite (Anderson and Hunt, 1964; DeMille, et al., 1964; Parker, 1967). Overlays constructed from isopach map presented by Anderson and Hunt do not show good correlation with tonal features on ERTS imagery.

Hazy areas:

- Both bands 4 and 5 seem to have hazy regions some of which are difficult to distinguish from tonal features.
- Hazy areas do not correspond to known production sites although some are within 5-10 miles of such sites (fig. 21).

Conclusion - Area A:

- Reliable targets for petroleum exploration could not be identified solely from ERTS-1 imagery.

Area B - Nesson and Antelope Anticlines

This region is largely overlain by Wisconsinan glacial deposits some of which are stagnant-ice moraines containing numerous small lakes. The ice margin generally paralleled the course of the Missouri River. Locations of the Nesson and Antelope Anticlines and an interpretation of their structural make up were presented previously on Figures 17 and 18 from Erickson (1970a). Production on these structures is mainly from Mississippian limestones.

Image 1245-17175 was used for much of the interpretation proposed here; the conclusions however result from examination of seasonal imagery of other portions of the area as well.

Linears:

- This region contains numerous rectilinear and curvilinear features (fig. 22).
- None occur over the major structures, a fact which is rather anomalous in itself, particularly in view of the fact that each structure is known to be faulted at depth (Folsom, et al., 1959; Bateman, 1957).

- Linears mapped by Erickson (1970a) could not be identified on the imagery.

Tones:

- Tones described here from March imagery (no snow cover) are subtle and complex.
- Tones are linear, irregular, and circular in shape.
- The March color composite "summarizes" tone patterns well, much better than does summer imagery. Black and white imagery is useful to "subtract out" some tone types allowing easier detailed mapping.
- As Figure 22 indicates, circular or elliptical tonal patterns are numerous. Many of these have been related to areas of stratified glacial deposits as mapped by Colton, et al., (1963).
- Non-circular tonal patterns also are related to moraine complexes and meltwater drainage systems. Not all tones can as yet be explained.
- Distribution of glacial deposits, particularly deposits relating to meltwater drainage seen by comparing maps by Colton, et al., (1963) and Bluemle (1972) with Bluemle's (1971) map of topography of the bedrock surface in North Dakota, has been controlled to some degree by pre-existing bedrock and structure. This control generally follows the NW and NE regional linear patterns seen in our study and in those of A.K. Erickson (1970a,b).

Hazy areas:

- Several hazy features are present on band 4 of image 1245-17175 (fig. 23).
- Because of numerous tonal variations on this image, hazy features are difficult to discern with certainty.
- Some hydrocarbon production occurs in "hazy areas" but correlations are not decisive.
- It appears possible that a wide variety of soil types and consequent variations in water content of soils may be responsible for the variety of tones and hazy-like features seen on this image.

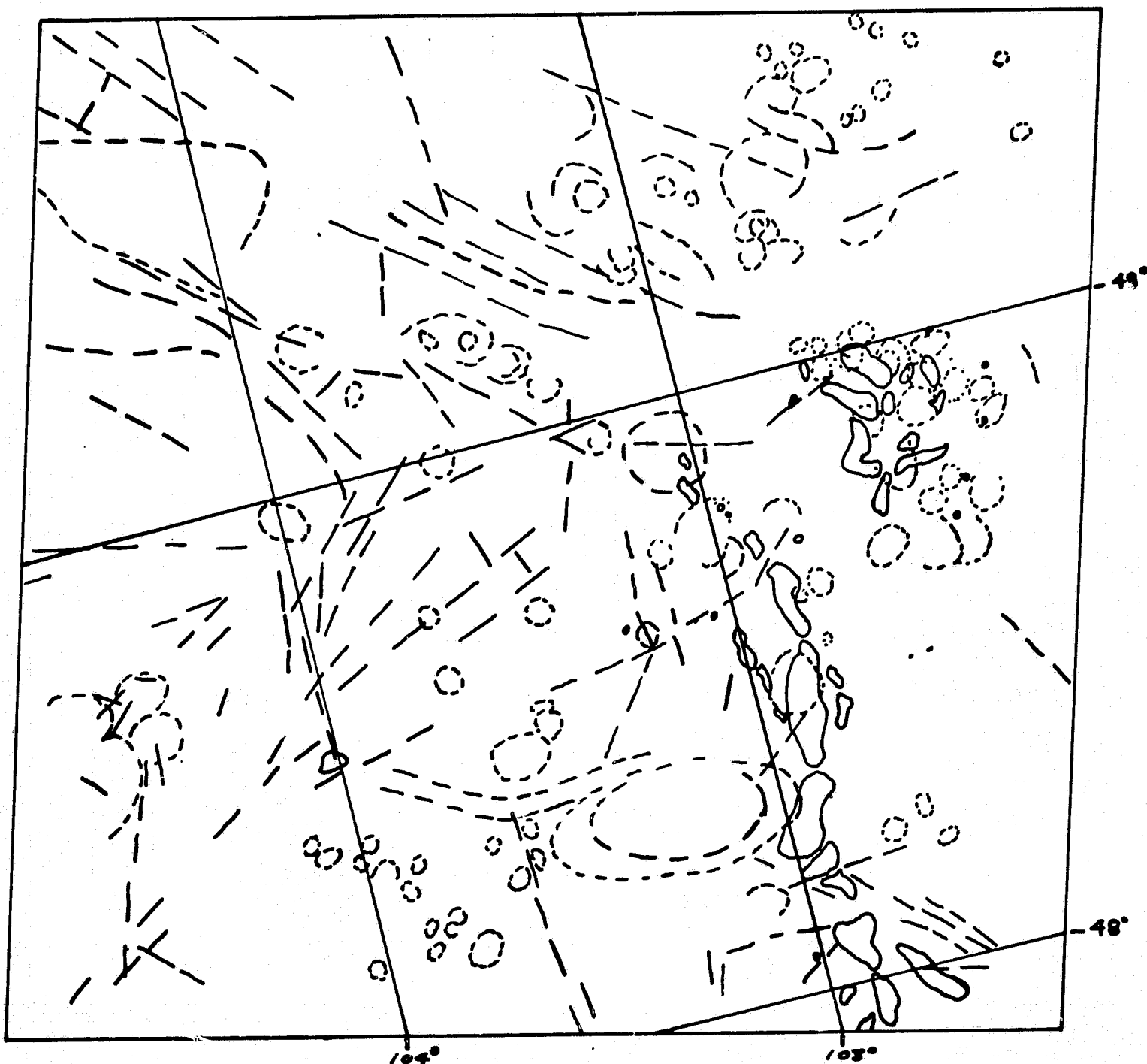


Figure 22. Composite map of Area B displaying linear and tonal features from all bands of image ID 1245-17175. Oil fields shown as solid closed lines.

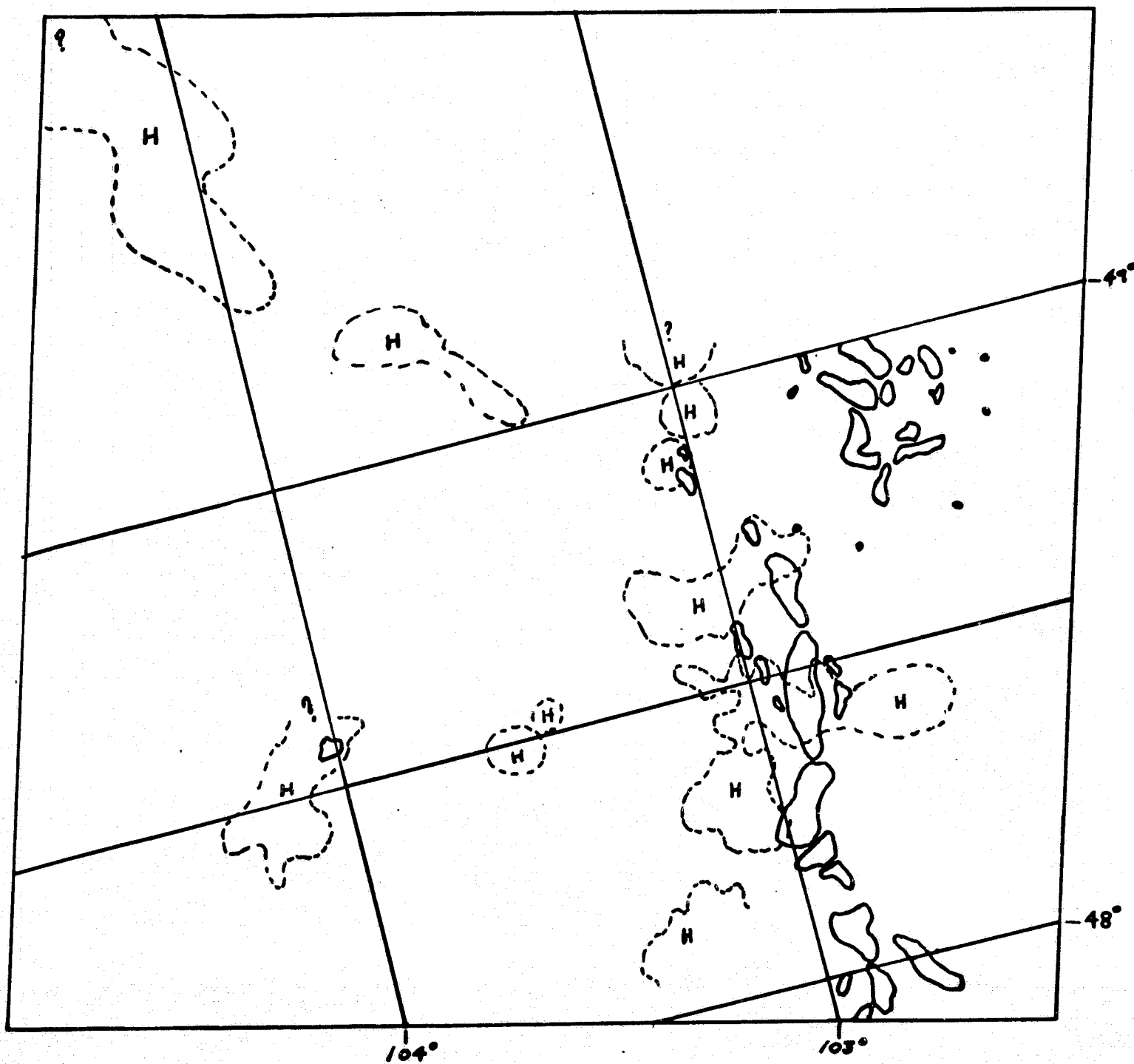


Figure 23. Map of Area B giving locations of hazy regions from band 4 of image ID 1245-17175.

Conclusions - Area B:

- Glacially - originated deposits mask bedrock structure and cause lack of definition of structure on this image.
- Identification of areas presently producing hydrocarbons was not possible from ERTS-derived data.

Area C - Redwing Creek Region

This region was examined on image 1263-17181, April, 1973, and portions were re-examined on summer and snow-covered winter imagery. Portions of three major oil-producing regions occur on this image. The Nesson-Antelope production and the Cedar Creek production are mentioned in discussions of Areas B and D respectively. The Dickinson oil fields lie in the SE corner of the image where oil is produced from Pennsylvanian "shoe-string" sands associated with the Tyler Formation. Principal interest, however, is focused on the Redwing Creek oil field, a relatively new discovery of limited size about which much speculation has arisen.

Most of this region was not covered by Wisconsin ice and therefore the imagery may be expected to more accurately record bedrock-related features. Shales and sandstones of late Cretaceous and Tertiary age characterize the predominant rock types. High plains topography, isolated buttes, and complex erosional surfaces of the Little Missouri badlands are standard geomorphic expressions on image 1263-17181.

Linears:

- Linear features are abundant on this imagery (fig. 24).
- Rectilinear stream segments are prominent. A prevailing NW and NE trending pattern indicates control of drainage by regional fracture (?) patterns.
- Short tonal linears are common.

- Erickson (1970a,b) mapped thirteen lineaments, each more than 30 miles long, in the area covered by this image (fig. 25). It is possible to identify segments of six of these "lineaments" including Brocton-Froid, Cedar Creek, Bismarck, Yellowstone, Little Missouri, and Redwing Creek. No positive identifications of structural offset has been defined along any of these features, although drainage patterns seem to change along or against some prominent linears.
- Most definite is the Cedar Creek lineament which will be discussed in Area D.
- Winter imagery with snow allows best study of the drainage patterns.

Tones:

- Spring (April) imagery presents several broad tonal areas which are grossly controlled by a combination of bedrock type and physiography. The Little Missouri badlands are an example.
- The "Golden Valley Low" a feature designated by Dow (1964) from subsurface studies may be represented by a region of cropland surrounded by unfarmed terrain at the center of the southern border of the image.
- Circular tonal features five to fifteen miles in diameter are abundant on the image and are seen best on the color composite. Many are located in hazy regions. Although some circular tones seem to be controlled by drainage and may thus be geomorphic in origin, none can be explained with assurance.
- Summer (July) imagery is less useful for recording circular tones.
- Only the Redwing Creek oil field seems to correspond closely to a circular tonal feature. It is discussed in detail below.

Hazy areas:

- The entire Yellowstone River drainage is "hazy" on band 4 of image 1263-17181. This region includes many of the circular tonal features mentioned above.
- There is no indication that the hazy region is related to existence of hydrocarbons at depth.

Redwing Creek oil field (fig. 24):

- The field was originally identified as a prospect for oil exploration by Erickson (1970a) on the basis of a complex subsurface interpretation of faulting from several dry holes. He defined the Redwing Creek lineament from aerial photo

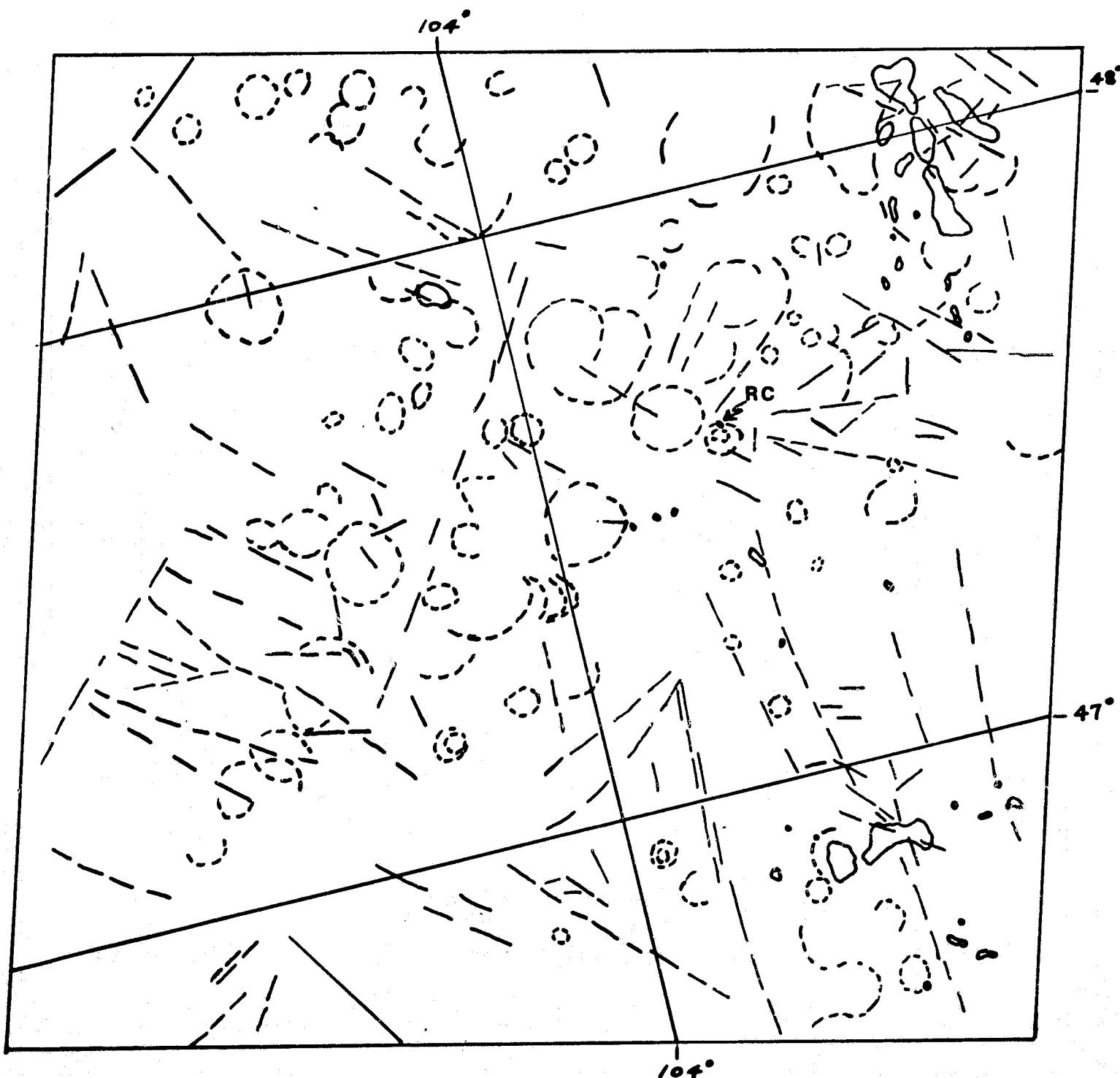


Figure 24. Composite map of Area C displaying linears and tonal features from all bands of image ID 1263-17181. Oil fields shown as solid closed lines. "RC" refers to Redwing Creek oil field.

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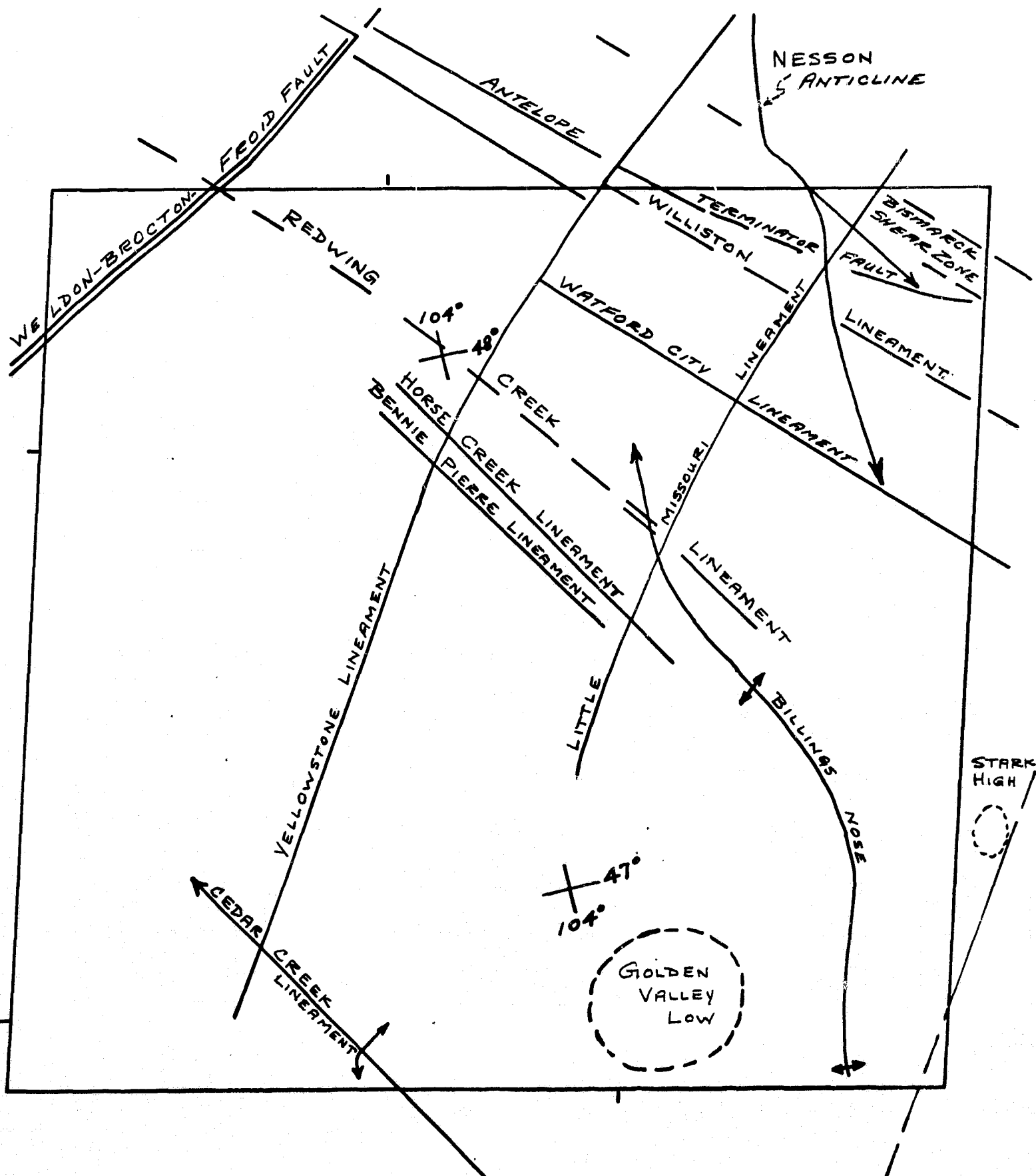


Figure 25. Sketch map of lineaments in Area C covered by image ID 1263-17181 as interpreted by A.K. Erickson (1970a).

studies and felt that it was the trace of the fault noted in the well logs.

- The structure was subsequently drilled by True Oil Company to produce a small (9 wells) field in Mississippian limestones. Of note, however, is the fact that the discovery well contained 3000 ft. of gross pay section.
- Sawatzky (1975) has reinterpreted the subsurface structure based upon the newly available data. The zone of production is a complexly disturbed, generally elevated section which he believes represents a combination of meteorite impact and subsequent salt collapse structure, the producing wells lying on the central rebound area of the impact crater.
- Although evidence for post impact salt solution is not clear, nor terribly pertinent, evidence for astrobleme origin is more compelling if reports are true. It appears that shatter cones have been recovered in cores from this structure (Sawatzky, 1975, p. 710).
- ERTS imagery records a double ringed tonal feature which, according to our abilities to discern exact geographic locations from the imagery, seems to lie at the location of the supposed Redwing Creek Astrobleme oil field.
- The image also records numerous faint linears in the area. None passes directly through the tonal feature but some strike in that direction.

Conclusions - Area C:

- Neither the Dickinson production nor the Nesson-Antelope structures could be identified as exploration targets based upon our analysis of ERTS imagery.
- We are not in a position to interpret the origin of the Redwing Creek structure herein. We note, however, that there are numerous circular tonal features on this image (1263-17181) similar in size and appearance to that which appears to correspond to the Redwing Creek structure.

Area D - Cedar Creek Anticline

In the Williston Basin the only major structure with extensive surficial expression recorded by standard mapping techniques is the Cedar Creek Anticline (fig. 4), a NW-SE oriented asymmetric structure most of which lies

in Montana. The entire anticline lies beyond the limits of glaciation in the basin. Cretaceous Pierre Shale is exposed along the axis and is flanked successively by Fox Hills sandstone and continental deposits of the Hell Creek Formation and the Tertiary Fort Union Group. The asymmetry of the structure and description of faults in well interpretations have led to acceptance of the belief that the anticline is the surficial expression of a deep seated basement fault which has periodically been reactivated. Unconformities are found in several Paleozoic and Mesozoic time intervals during which the surrounding area was receiving normal sedimentation. No clear documentation of the trace of the Cedar Creek fault has been recorded to our knowledge although limited segments may have been recognized in the field.

Oil and gas are produced along the entire length of the Cedar Creek Anticline. The oil is largely derived from Ordovician source rocks (Dow, 1974) but reservoirs may include several younger formations. Cross-faults trending NE across the axis have been mapped and seem to subdivide the anticline into secondary elongate domal structures best expressed by variations in hydrocarbon traps at depth (Gwynn, 1964; Erickson, 1970a).

Image 1047-17173 (Sept. 1972) was used for detailed analysis supplemented by image 1335-17180, a June image used for seasonal comparison. The September image is an excellent example of an image from which geologically useful information may be gleaned, particularly from the color composite.

Linears:

- Linears are frequent on the imagery. They clearly define the NW and NE trends discussed under Linears and Lineaments in this report.

- Several linears can be related to subsurface structural control and may be termed true lineaments. Foremost among these is the Cedar Creek lineament, a sharply defined, light tonal line (fig. 26) which terminates abruptly at the Yellowstone River Valley.
- At least two NE-trending lineaments are traces of cross faults cutting the more southerly portion of the anticline.
- Linears mapped by Erickson in 1970(a) correspond well with major linears mapped during our study. The ERTS imagery records many more linears than were included in Erickson's study.

Tones:

- September imagery recorded large and small tonal features. Large features may define major structural elements because they appear to be representative of bedrock types and may thus be mappable.
- The Cedar Creek Anticline is defined as a long, dark tonal element on the imagery. The Cedar Creek lineament defines the western edge of this tonal pattern whereas the eastern edge blends less distinctly into bordering tones.
- Cross faults can be defined by offsets in this tonal pattern.
- The "Golden Vallow Low" of Dow (1964) appears as a subcircular region of light-colored cropland surrounded by darker tones on the north-central margin of the September image.
- Circular tonal features of unknown origin appear on the image but are less common than in areas previously discussed.

Hazy areas:

- No hazy features are found on the September imagery.
- Summer imagery showed a few hazy areas - none on petroleum production sites - which may have resulted from thin cloud cover.

Drainage pattern:

- The drainage pattern on this image is worthy of note. We believe it is strongly influenced by regional structure and has interpretive value beyond that of other regions studied in this report.

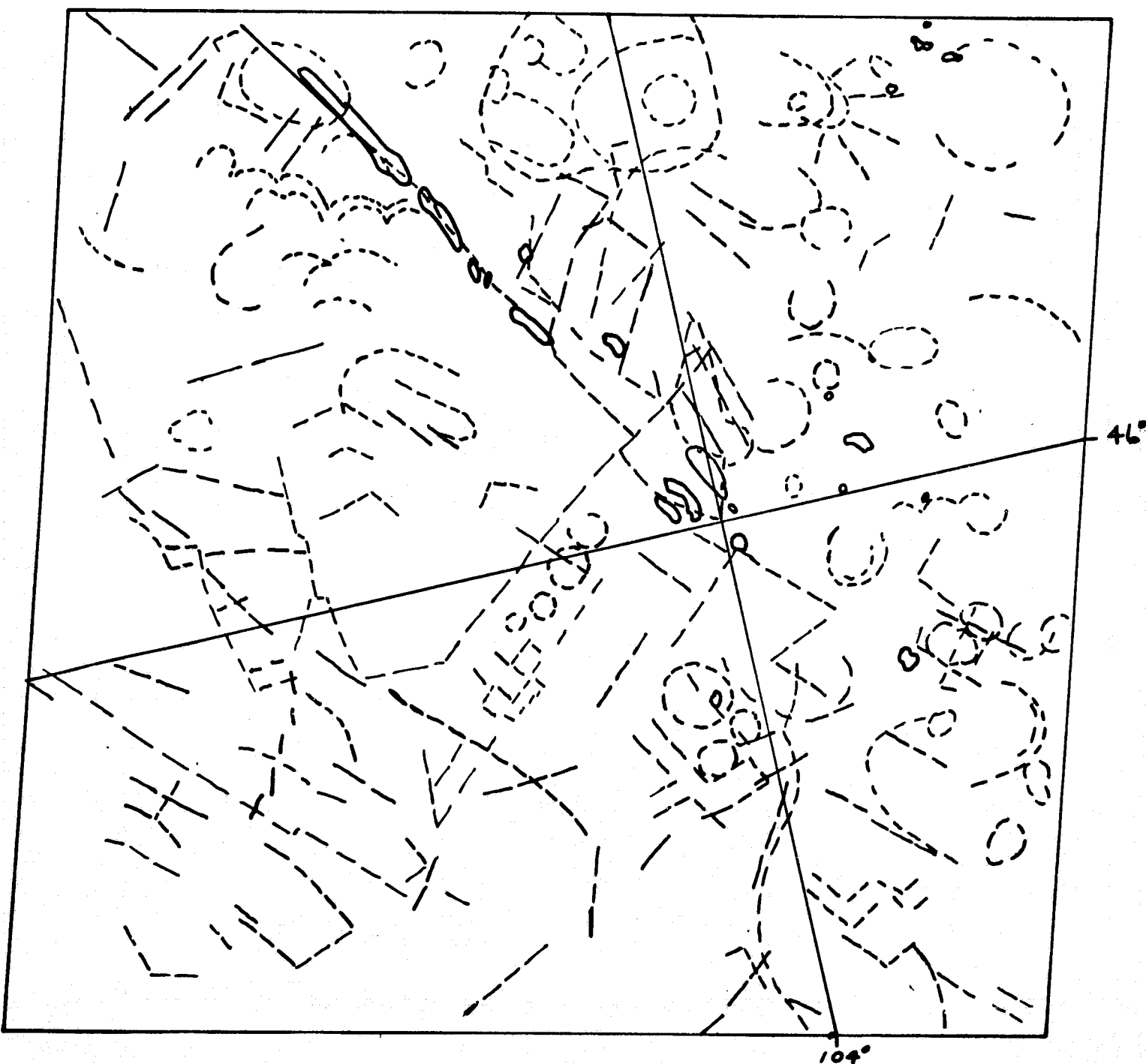


Figure 26. Composite map of Area D displaying linears and tonal features from all bands of image ID 1047-17173. Oil fields shown as solid closed lines.

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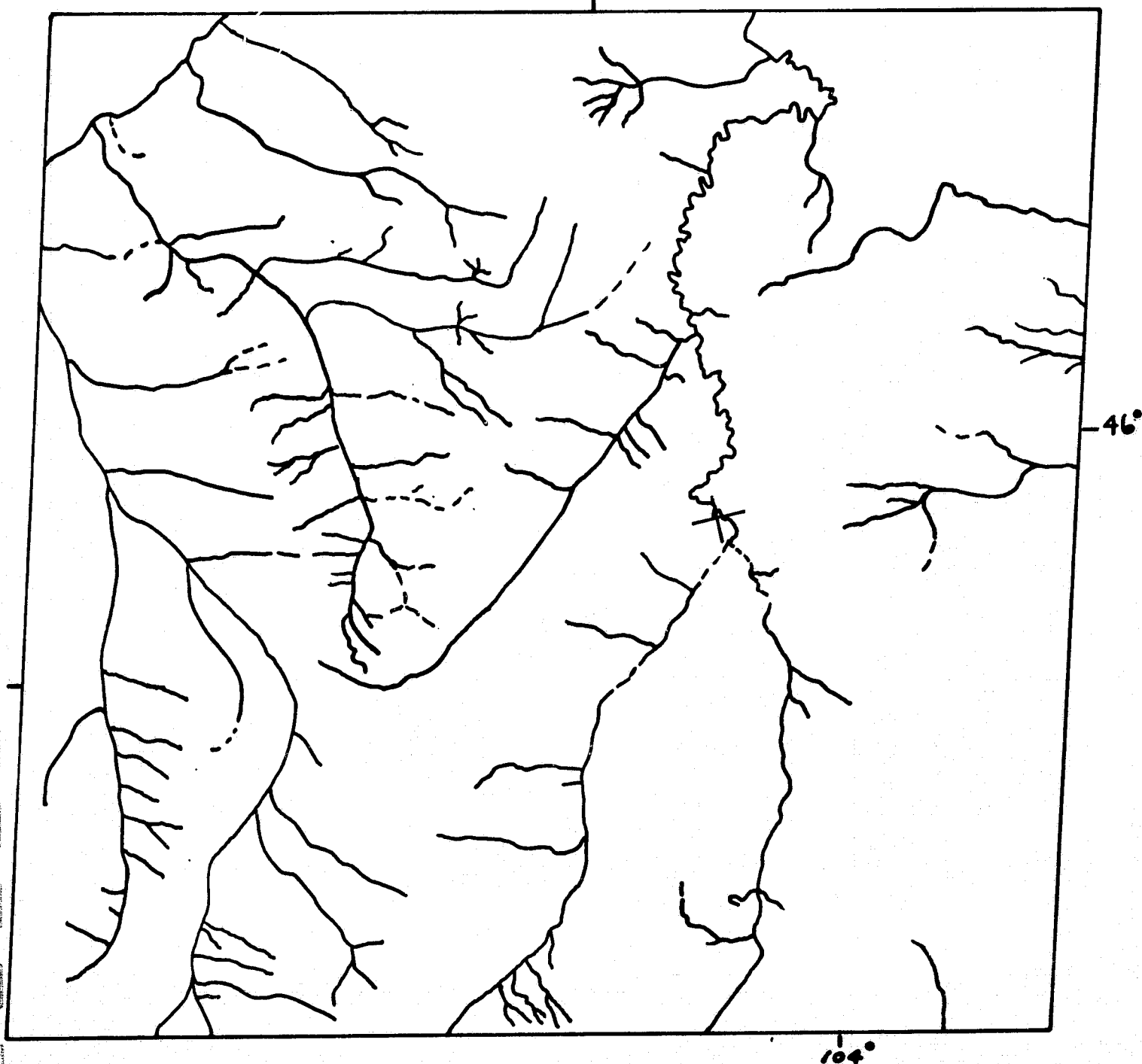


Figure 27. Map of principle drainage net in Area D taken from image ID 1047-17173.

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- Figure 27 traces the major drainage patterns of the region and illustrates the NW and NE trends present west of the Cedar Creek anticline.
- Drainage has proven useful in other areas of the basin during our study and we believe its exploration potential should be utilized further.

Conclusions - Area D:

- ERTS imagery could definitely be used to define exploration targets for hydrocarbons in this area.
- Linears, tonal features, and drainage pattern should be combined in such a study.
- Spring or Fall rather than Summer imagery will be most useful.
- Band 4 is least likely to be helpful and the color composite will be the most helpful.

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